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THE EMR/NSPC AFBC MATERIALS PROGRAM: EVALUATION OF THE PROBES REMOVED AT THE END OF RUN 9

J.B. GILMOUR, A.W. LUI, D.C. BRIGGS AND R.F. KNIGHT
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THE EMR/NSPC AFBC MATERIALS PROGRAM: EVALUATION OF THE PROBES REMOVED AT THE END OF RUN 9

by

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ABSTRACT

At the end of the ninth one thousand-hour run of the Point Tupper atmospheric fluidized-bed combustor pilot plant operated by the Nova Scotia Power Corporation, in-bed Probes 2B2, 4B1, and 9DL3 were removed after having been exposed for 5000, 8000, and 4000 h respectively. The coupons from these probes have been examined in the laboratory and the results of the initial examination are contained in this report.

LABORATOIRES DE RECHERCHE EN MÉTALLURGIE PHYSIQUE

RAPPORT:PMRL 86-39(TR)

LE PROGRAMME DE EMR/NSPC SUR LE COMPORTEMENT DES MATÉRIAUX DANS LES CHAUDIÈRES À LITS FLUIDISÉS: ÉVALUATION DES SONDES RETIRÉES À LA FIN DU 9e ESSAI.

par

J.B. GILMOUR, A.W. LUI, D.C. BRIGGS and R.F. KNIGHT

RESUME

Neuf essais d'une durée de 1000 h chacun ont été effectués à l'usine pilote de Point Tupper pour la combustion du charbon à l'état fluidisé sous pression atmosphérique. L'usine est dirigée par la Nova Scotia Power Corporation. A la fin du 9e essai, les sondes 2B2, 4B1 et 9DL3, ont été retirées après avoir été exposées dans le lit pendant 5000, 8000 et 4000 h, respectivement. Les résultats préliminaires de l'examen des échantillons inclus dans ces sondes sont présentés dans ce rapport.

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INTRODUCTION

This report contains the results of the preliminary metallurgical examination of the probes removed at the end of the ninth run of the Point Tupper Atmospheric Fluidized-Bed Combustor operated by the Nova Scotia Power Corporation. References 1, 2, 3 and 4 should be consulted for background information on this project. Reference 5 gives details of the specimen design and the procedures followed in the preparation and examination of the specimens. The results contained in this report are confined to the determination of metal loss, scale formation, descriptions of the specimens, metallographic observations etc. No detailed analyses of the mechanism of attack will be given. Additional work such as electron probe microanalysis, scanning electron microscopy, deposit and scale analysis etc. will be required before comments regarding mechanisms can be made. This additional work will be reported separately at a later date.

The probes discussed in this report are 2B2, 4B1 and 9DL3. Figure 1 shows the location of these probes in the combustor. Probe 2B2 was installed in the combustor at the start of the fifth run (84-07-17), and was removed at the end of the ninth run (85-04-18) after a total exposure of 5000 h. Probe 4B1 was installed at the start of the second run (84-01-05), and was removed at the end of the ninth (85-04-18) after an exposure of 9000 h. Both these probes were air-cooled controlled-temperature probes operating with a steady-state temperature gradient along the probe of from 550 C to 700 C. Probe 9DL3 was installed at the start of the sixth run (84-09-15) and was scheduled to be removed at the end of the tenth run after a 5000-h exposure. However, it had been noted at the end of run 8 that both coupons 1 and 6 had a few areas of apparent sulphidation attack. Nevertheless, the probe was reinstalled for the ninth run. At the end of the ninth run (85-04-18) coupon 1 was found to be extensively corroded and the probe separated at the coupon 1-2 joint when it was removed from the combustor. This precluded the probe being reinstalled for the final run and thus, this probe was exposed for only 4000 h. Photographs of probe 9DL3 taken at the end of both runs 8 and 9 are given later in this report.

Details of the operating conditions in the combustor during runs 2 to 9 are contained in the various reports issued by NSPC for these runs.

This report is divided into several sections. The temperature data of the specimens will be discussed first, followed by the oxygen partial-pressure measurements. This will be followed by a general description of the probes as removed from the combustor. The results obtained in the metallurgical evaluations will be discussed, and summary tables and diagrams given of metal loss, bore scale, internal attack, etc. as appropriate. The detailed results of the measurements on each coupon are found in Appendices 1, 2 and 3 which consist of individual data sheets and two photomicrographs for each coupon in probe 2B2, 4B1 and 9DL3 respectively. Many of the measurements from the data sheets are also found in the summary tables, and appropriate corrections have been applied in some cases. These corrections are discussed in the body of the report.

COUPON TEMPERATURES

As is the standard operating procedure of the pilot plant, the eight thermocouples in probes 2B2 and 4B1 (top and bottom of coupons 3, 8, 13, and 18) were read each minute by the data logger, and the hourly averages, minima, maxima and standard deviations printed out. NSPC has calculated average temperatures for each thermocouple for each run and an overall average for each thermocouple. These averages for probes 2B2 and 4B1 are given in Tables 1 and 2. Complete details of the temperature history of these probes can be found in the NSPC report on the process and test specimen temperature data (6).

The temperature distribution along probe 2B2 is similar to that observed for other probes reported earlier in that the top of the probe is consistently hotter than the bottom. The maximum average temperature difference was 72 C on coupon 3. This differential decreased along the length of the probe to a minimum of 8 C on coupon 18. The temperature distribution along the probe was relatively stable for the five runs (Table 1) although thermocouples 2 and 4 do show an increase in temperature between runs 6 and 7. Also, the top to bottom difference of coupon 18 increased with time.

The temperature data for probe 4B1 are quite different from those of 2B2. At coupon 3 the top was 87 C hotter that the bottom but the difference decreased to only 10 C on coupon 8. Coupon 13 and 18 exhibited higher temperatures on the bottoms of the coupons than on the tops; 27 C on coupon 13 and 14 C on coupon 18. This is the first probe examined in detail that exhibited

this reversal of top to bottom temperatures. However, NSPC data have shown that most B probes on the east side of the combustor have temperature profiles similar to 4B1 in that at the north end of the probes the bottom is hotter that the top. This may be related to the flow pattern in the bed; more particularly an increased flow of air through the east side of the combustor than through the west side.

As can be seen from the data in Table 2, the run-average temperatures of the thermocouples decreased from runs 2 through 7 (75 C on thermocouple 4), then increased and remained stable during runs 8 and 9. Thus the thermal history of the coupons in this probe is more complex than that of the coupons in most probes.

Representative top and bottom temperatures for each coupon have been calculated from the thermocouple temperatures by interpolating between the thermocouples and extrapolating to the end coupons (always assuming a linear relationship between the coupon position and temperature). The calculated average temperatures for each coupon in probes 2B2 and 4B1 are given in Table 3 and 4.

The "D" probes are not cooled and probe 9DL3 was therefore assumed to operate at the bed temperature, nominally 850 C. During run 3 a thermocouple was inserted through the end fitting of the D probes and the temperature measured every 10 cm along the probe. These thermocouples registered 10 to 15 C below bed temperature. However, for purposes of discussion, the temperature of all coupons in D probes are assumed to be 850 C. There cannot, of course, be any significant top-to-bottom temperature difference in an uncooled probe.

OXYGEN PARTIAL PRESSURE MEASUREMENTS

The pilot plant is equipped with a Fluidyne oxygen monitoring system (oxygen probe) that allows the measurement of the oxygen partial pressure in (and above) the fluidized bed. (The term "oxygen partial pressure", or "pO_2", will be used in this report although it is recognized that the signal developed by the sensor may not be dependent only on the true oxygen partial pressure.) The ports normally available for oxygen mapping are shown in Fig. 1 (light circles). Oxygen partial pressure measurements from ports B6 and E9 should give an indication of the conditions close to probes 2B2, from port G13 and I9 an indication of conditions close to probe 4B1 and ports C3, B6

and E9 an indication of conditions near 9DL3. Port B6 was adapted for oxygen mapping only at the end of run 6. During run 9, port D2 (the normal probe 10DL location) was adapted for oxygen mapping and consequently ports E1 and C3 were not accessible. Oxygen probe data from run 9 were not available when the figures for this report were prepared. However, as noted below, the data for runs 8 and 9 were very similar.

Figures 2 to 6 (upper plots) show representative "Logarithmic Average"
oxygen partial pressure plots as calculated by the Fluidyne computer program for the relevant ports mapped during runs 3 to 8. It is recognized that the physical significance of the "logarithmic average" values given by the program is open to question. Therefore, the percentage of time that the pO_2 was less than 10^{-10} atmospheres has been plotted (Fig. 2 to 6, lower plots) for the same ports/ runs/ data-sets. The data for these "percentage of time" plots were obtained from the histograms produced by the Fluidyne software. The error in picking the data points from the histograms is perhaps +-2%. The choice of 10^{-10} as the limiting oxygen partial pressure was based on expediency: the histograms have a grid line at this value. The use of 10^{-12} as recommended by Battelle (7) would not have made a great difference to the shape of the resulting plot, but it would have been somewhat more difficult to extract the data from the histograms.

It will be seen that the two methods of plotting the data produce essentially mirror images (about the X-axis) of the plots. Thus, either method of presentation appears to give an equally useful indication of areas of low or high pO_2. Undoubtedly, from an interpretive point of view, the "percentage of time" plots have a greater physical significance than the "logarithmic average" plots.

In earlier reports in this series, the pO_2 plots for various ports for one run were plotted in the same figure. Because of the number of runs covered by this report, it was considered preferable to plot the data from the same port, but for different runs, in the same figure. This method of presentation gives a better indication of the variation of conditions at the various oxygen probe ports.

During runs 5 and 6 it was noted that the pO_2 distribution for ports on the west side of the combustor was very different from that which had been

observed during earlier runs. At the end of run 6 it was discovered that the opening of the coal/ limestone feed nozzle toward the south-west corner of the bed was blocked and thus, all the fuel for runs 5 and 6 had been injected into the north-east corner of the bed. The effect of this is most noticable in the plot for port C3 (Fig. 6). The plots for ports on the east side of the bed also reflect this undesirable condition, but not to the same extent as those on the west side.

During the early part of run 7 the fuel-feed nozzle was rotated and oxygen mapping carried out with the nozzle 15 degrees off the bed diagonal (rotated clockwise when viewed from above) as well as rotated 90 and 180 degrees. Details of the oxygen partial pressure distribution under these non-standard conditions can be found in the NSPC report for run 7 oxygen mapping. However, as the very unusual condition that existed when the nozzle was rotated by 90 degrees existed for only a few hours, this, and other non-standard conditions, will be ignored in this report.

The oxygen probe data for ports E9 and B6 (Fig. 2 and 3) give some indication of the conditions near probe 2B2. During the first 2000 h exposure of this probe (runs 5 and 6), the conditions would have been very oxidizing as a result of the plugging of the opening of the nozzle pointing into the south-west corner of the bed. However, the north end may have experienced somewhat reducing conditons, judging from the data from port E9 (Fig. 2). During runs 7, 8 and 9 the south end was probably reducing (note plot for port B6). In addition to the information given in the pO_2 plots, it should be remembered that during run 8 probe 9DL3, located immediately below probe 2B2, developed areas of sulphidation type attack on coupons 1 and 6 and that during run 9 this attack intensified greatly, especially on coupon 1. It would be expected that the coupons at the south end of probe 2B2 would have been exposed to conditions similar to those that caused the failure in probe 9DL3. The oxygen probe data for port E9 gives some indication of these very reducing conditions.

Probe 4B1 was exposed during runs 2 to 9 for a total of 8000 h. Oxygen probing of ports I9 and G13 was not done during run 2, but it is believed that conditons during run 2 were similar to those during run 3. (Also, data from run 9 is very similar to run 8.) It will be noted that the pO_2 for port G13 (Fig. 5), the closest port to probe 4B1, shows that conditions varied rather considerably from one run to another, but within a relatively well de-

fined range. Port I9 (Fig. 4) also illustrates this band of data. However, interpolating between the data for these two ports to obtain an indication of the conditions near probe 4B1 introduces considerable uncertainty. It appears that the south end of the probe would have experienced more oxidizing conditions than the north end, but all the coupons were in what were expected to be relatively non-aggressive conditions.

Data from ports C3, B6 and E9 (Fig. 6, 3, and 2, respectively) must be used to infer the conditions at probe 9DL3. Unfortunately, none of these oxygen probe ports is particularly close to probe 9DL3. During runs 5 and 6 the conditions were very oxidizing and during runs 7, 8 and 9 the south end of the probe was in a very reducing zone. During run 8, coupons 1 and 6 (800H) of this probe developed areas of sulphidation type attack on the bottom, and during run 9 these progressed to the point of massive attack on coupon 1. Unfortunately, the pO_2 plots give little indication of the particular conditions responsible for this attack. Data for run 9 show that port B6 had conditions very similar to those during run 7. Port C3 was not available for oxygen probing during run 9.

DESCRIPTION OF THE PROBES

PROBE 2B2

Macrographs from four orientations of probe 2B2 after removal from the combustor are given in Figures 7 to 10.

Probe 2B2 had been in the combustor for 5000-h and appeared to be in excellent condition. The coupons were all aligned and remained tightly screwed together. The colour of the scale/deposit on the probe was primarily black, with a tinge of brown/red toward the north (high coupon number) end. The deposits varied greatly in thickness. The first few coupons had very thin deposits on the top but coupons 4 to 8 had heavier deposits. The bottom of the probe appeared to have no true deposit on the first 7 coupons but relatively heavy deposits on coupons 8 to 16. The sides of the probe had heavy deposits on coupons 4 to 18. Considerable spalling had taken place on some coupons, with spalling both to intermediate layers and to the alloy surface.

PROBE 4B1

Macrographs from four orientations of probe 4B1 after removal from the combustor are given in Figures 11 to 14.

Although this probe had been in the combustor for 8000 h, it appeared to be in excellent condition. There was a slight (few mm) bow upward, with bending concentrated at joint 18/19. The probe was "overtightened" by about 20 degrees but this had occurred earlier in the program. When removed from the combustor, joints 8/9 and 19/20 were only hand tight, but there was no indication of any relative movement of the coupons during the last run.

The deposits were sufficiently thick on the tops of the coupons that the punch marks/scribe line could not be seen. Deposits were generally brown/black and on some coupons had appreciable thickness (perhaps 1 mm). Although the surface of these heavy deposits was smooth, it was frequently stepped, an effect believed to be caused by scale/deposit spalling and reforming during exposure. Deposits were quite thin on the top of the first few coupons (south end) and the weld was visible in coupon 1. The deposits became thicker along the probe and were especially thick on the T91 coupon 6. The deposit thickness then seemed to decrease gradually toward the north end of the probe (high number coupons). Considerable spalling to the alloy surface had taken place, especially on sides of coupons where deposits underwent a transition from thick top deposits to very thin bottom deposits. The bottoms of coupons 1 to 10 of this probe were covered with a thin, brown/black scale. Above coupon 10 deposits had spalled in many areas exposing a grey scale. However this spalling was of a very different type than that of the heavy deposits on the top of the probe. On the bottom, deposit had spalled in very small flakes rather than in large areas as on the top. In addition, spalling on the bottom was to a grey scale, not to the alloy surface. There was a defined transition in the deposit/scale between the top and the bottom of coupons along the sides of the probe.

The bottom of coupon 2 had a diagonal band of thick deposits across the coupon that was related to the very close proximity of a thermocouple well in the combustor.

There was a noticable loss of metal from the 304H and N82 of coupon 1 relative to the T91 (of coupon 1) and the 347H extension. Also, the N82 weld metal of coupon 7 had noticably receded relative to the 304H and T91 of the same coupon.

PROBE 9DL3

When this probe was removed from the combustor at the end of run 8, some areas of relatively heavy corrosion were found on coupons 1 and 6 (both 800H). Photographs of these coupons taken at that time are shown in Fig. 15 and 16. The corroded areas appeared to be sulphidized and corrosion penetrated as deep as perhaps 1 mm on the bottom of coupon 1. Coupon 6 had a smaller, but similarly appearing, region on the side of the coupon. The corroded areas on both coupons were of limited extent and the rest of these coupons appeared to be in good condition. It was decided to replace the probe in the combustor in an attempt to reach the originally-planned 5000-h exposure. However, when this probe was removed from the combustor at the end of run 9, coupon 1 was found to be extensively corroded (Fig. 17 and 18) to the extent that the probe came apart, and coupon 6 had areas of heavy corrosion (Fig. 19). Coupon 2 was also heavily corroded in areas adjacent to the corroded areas of coupon 1. Macrographs from four orientations of probe 9DL3 after removal from the combustor are given in Figures 20 to 23.

At positions 1 and 7 (approximately) of the joints between coupons 6/7 and 8/9 there were small areas that appeared to have corrosion products on the surface that originated within the crevice between the coupons.

With the exception of coupon 1, the adjacent areas of coupon 2, and coupon 6, the probe appeared to be in good condition. The top of the probe showed a "flow pattern" extending from coupon 1 to coupon 12. (This pattern is visible in Figures 20, 21 and 22). The top of the probe in this region was generally a dull brown colour, whereas the sides were more red/brown. The north end of the probe (higher numbered coupons) was grey/black and mostly deposit free. The last few coupons had patches of a shiny brown deposit on the top and sides and a trace of dull brown deposit on the bottom. It appeared that more of the surface had been covered with these, or similar, deposits and that these had spalled from the surface. Traces of heavier brown deposits were found on other coupons. The bottom of the probe was generally brown/black at the south end and grey/black at the north end. Few deposits were retained on the bottom surface.

The probe had a bow upward of a few millimetres, having bent primarily at joints 11/12 and 12/13. The coupons were all aligned correctly when removed from the combustor with the exception of course of joint 1/2 where the probe had come apart on removal. The perforation of coupon 1 allowed the bed environment free access to the bore of coupons in this probe.

LABORATORY EVALUATION

After receipt in the laboratory, the probes were coated with polyester resin where they were to be sectioned and then dismantled at joints that would unscrew without great difficulty; Table 5 lists these joints on the three probes. The coupons were subsequently sectioned, mounted, polished and measured as described in reference 5. The data obtained during the examination of these three probes, along with two photomicrographs of each specimen, are contained in Appendix A1 for probe 2B1, Appendix A2 for probe 4B1 and Appendix A3 for 9DL3 (see the following section for a discussion of the data sheets of the Appendices).

To correct the "metal loss" data for the one ferritic alloy, T91, for the oxidation of the bore (air side) of the probe, one half the thickness of the bore scale has been deducted from the "metal loss" to obtain the "corrected metal loss" used in calculating the total attack. (A simple calculation will show that, assuming the formation of only Fe_2O_3 the theoretical correction factor is 0.47, assuming Fe_3O_4, 0.48 and assuming FeO, 0.56.) Whenever possible, the bore scale of the stainless steel coupons has been ignored when making the measurements of the remaining metal, and thus, no correction has been made for bore scale on the austenitic alloys. Where significant internal attack occurred, the internal attack has been added to the "metal loss" (austenitic alloys) or "corrected metal loss" (ferritic alloy) to obtain the "total attack" or "total fireside attack".

Metal loss, internal attack and total attack for Probe 2B2 are given in Tables 6 to 8 and plotted in Figure 24 to 26. Metal loss, internal attack and total attack for Probe 4B1 are given in Tables 9 to 11 and plotted in Figure 27 to 29. Metal loss, internal attack and total attack for Probe 9DL3 are given in Tables 12 to 14 and plotted in Figure 30 to 32. Generally, all measurements have been made or rounded off to the nearest 5 µm. Where the value measured is 7 µm or less, "TR" for "trace" has been recorded, and this has not been used in corrections. Values of 8 µm have been rounded up to 10 µm and used in corrections. The values in Tables 6 to 14 have been used in plotting Fig. 24 to 32. (NOTE THAT THE SCALES IN THE PLOTS ARE NOT ALL THE SAME.)

It is not the purpose of this report to analyse in detail the results obtained. Additional work including electron probe microanalysis, X-ray dif-

fraction analysis of scales and deposits etc. are required before conclusions can be made. However, based on the results given in this report, it is possible to make some general, but preliminary, comments.

Probes 2B2 and 4B1

Before considering a comparison of the attack of probes 2B2 and 4B1 with other probes it is instructive to look at the plots of total attack for these probes, Fig 26 and 29 respectively. It is immediately obvious that many of the coupons in probe 4B1 suffered accelerated attack on the bottoms of the coupons (position 4) whereas the coupons in probe 2B2 do not show this effect. Thus, it appears that the bottoms of coupons in probe 4B1, at least from coupon 3 to coupon 16 have suffered from an erosion-related metal loss similar to what has been observed on many of the A probes reported on earlier in the program.

Table 15 compares the rates (in μm/a) of total attack of the coupons in probes 2B1 (removed at the end of run 4 after 3000 h exposure) with those of the coupons in the probes removed at the end of run 9; 2B2 after 5000 h and 4B1 after 8000 h. In this table, the average rate of attack (average of the 8 positions measured) and the maximum rate of attack of each coupon are grouped by alloy. Generally, the same numbered coupon in each probe has been exposed at a similar temperature, although as discussed earlier in this report, the coupons in probe 4B1 have a different circumferential temperature distribution than do the coupons in the other two probes. However, ignoring these circumferential temperature distributions, one would expect an increasing rate of attack for each alloy along the probe if corrosion were the primary wastage mechanism. It will be noted that such a trend is not exhibited in this table. Also, if diffusion controlled corrosion mechanisms were dominant, the rate of attack should decrease with time. Although the average rates for 2B1 and 2B2 have a trend in this direction, those for probe 4B1 do not.

Considering these results in light of the normal oxygen partial pressure distribution in the combustor does not show any obvious correlation. For instance, coupon 3 of the 2B probes is in a location of low oxygen partial pressure (and thus, expected to be an area of high corrosive attack) whereas coupon 17 of these probes is in a location of normally high oxygen partial pressure. Yet coupon 3 has a lower rate of attack than coupon 17. Similar observations can be made for the other alloys.

Thus, it appears that there is no obvious correlation with oxygen partial pressure, or with temperature within the limited temperature range experienced by these probes. However, there are significant differences in the rates of attack, and, at least for probe 4B1, an indication that the high rates are the result of an erosion related mechanism. The location of the coupon within the combustor is probably very important in that erosion is expected to be dependent on the velocity or bed flow conditions in specific regions of the combustor.

However, it should be mentioned that the rates of attack of probes 2B2 and 4B1 are not very high. A rate of 330 μm/a is equivalent to 5 mm in 15 years, probably an acceptable maximum wastage rate for a utility superheater. Most of the maximum attack rates for 304H, 347H and 310 coupons are below this value, and thus, it is probable that minor differences in combustor design and/or operation would result in maximum rates below this value.

The metallographic examination of the specimens from these two probes revealed a somewhat unusual microstructure at some locations at the surface of many of the austenitic coupons. This microstructure is well illustrated in the photomicrographs of the bottoms of coupons 10 to 13 of probe 4B1 (pages A2-21 to A2-26). In these coupons there is a surface "zone" containing many fine globular sulphides and this zone appears distinctly separate from the parent austenite which, where the zone is well developed, does not appear to contain any sulphide/oxide precipitates or scale intrusions. However, within the zone, the size distribution of the sulphide precipitates varies across the width of the zone. Close to the inner (alloy) edge of the zone the sulphides are numerous and very small, whereas at the scale/metal interface they are fewer in number but larger, suggestive of an Ostwald ripening phenomenon. Coupons 10 to 13 include all the austenitic alloys in the "B" probes; 304H, 347H, 310 and 800H.

This zone in several of these specimens has been analysed with the electron probe microanalyser and the metallic matrix contains higher nickel than the parent alloy but very little chromium (e.g. coupon 4B1-11, 310, surface zone >45%Ni, <5% Cr). The globular precipitates are probably primarily chromium sulphide, although some contain manganese. More detailed microprobe and Auger analyses are being carried out and the results will be reported later.

Probe 9DL3

The results obtained with this probe will be compared with those from probes 9DL1 (1000 h) and 9DL2 (3000 h). All these probes were located in the same combustor port and thus, they provide an excellent comparison of the reproducibility of the corrosion conditions in one port of the combustor over a period of 8000 h.

The average and maximum total attack rates in μm/a for each coupon in probes 9DL1, 9DL2, and 9DL3 are given in Table 16. These data are plotted in Fig. 33 to 37, with the maximum and average attack for each alloy in one figure. Most of the coupons in these D probes do not show a significant increase in attack on the bottom of the coupons as do the coupons in the B probes discussed above.

It appears that the overall conditions during runs 3 to 5 (probe 9DL2) were less aggressive to all the alloys than those during run 2 (9DL1), or runs 6 to 9 (9DL3), as most of the tabulated rates are lower for probe 9DL2 than for probes 9DL1 or 9DL3. The 310 and 347H coupons performed significantly better than the other three alloys. If it were not for the attack on coupon 7 of probe 9DL1, the 347H would have performed marginally better than the 310. HK40 appears to be slightly more resistant to attack than 253MA, and 800H is obviously the most susceptible to attack.

There are some interesting contrasts between the performance of the alloys along the probes. Alloy 800H is obviously susceptible to catastrophic attack under certain conditions. Unfortunately, there are not sufficient data available from these runs to allow the definition of these conditions. During run 2 probe 10DL1 suffered catastrophic attack on coupon 6 and although the maximum attack on coupon 6 of probe 9DL1 was high, coupons 11 and 16 of this probe (which were in oxidizing regions of the combustor) also suffered high maximum attack rates. The 800H coupons in probe 9DL2 show a trend to higher rates at the north end (higher number coupons, normally more oxidizing conditions) although this may be the result of the very oxidizing conditions at the south end of the probe during run 5 when the SW opening of the fuel nozzle was blocked.

Most of the alloys in probe 9DL2 show a higher maximum attack rate at the north end of the probe than at the south end. Probe 9DL3 shows a similar trend for only 253MA and the reverse for 800H and 347H.

The oxygen probe data do not appear to correlate with the results for these three probes. The south end of the probe is usually in a zone of very low pO_2 whereas the north end is in an area of high pO_2. The results for the 800H coupons from probe 9DL1 appear to show some correlation with this distribution, but even the 800H coupons from the other runs do not. However, the pO_2 distributions measured during runs 8 and 9 when the catastrophic attack of the 800H coupons 1 and 6 (9DL3) occurred were not different from those during other runs, namely 3, 4 and 7, when the coal nozzle was functioning properly and yet massive attack of the 800H did not occur during these latter runs in the 9DL position. Thus, there appears to be significant differences in the conditions in the combustor from one run to another but the exact nature and causes of these differences are not immediately obvious from the data examined to date.

DATA SHEETS

A data sheet for each coupon of probes 2B2, 4B1 and 9DL3 is found in Appendices A1, A2 and A3 respectively. Two photomicrographs are given for each coupon, generally one from the top quadrant of the coupon (upper photograph) and one from the bottom quadrant (bottom photograph). The "position" numbers in the caption refer to the standard postion designation used in this work. Positions are numbered clockwise when viewed toward the south end of the probe with position 8 at the top. These photomicrographs are included in the Appendices on the page following the relevant data sheet. Please note that the magnifications are not all the same. Most of these photos were taken directly on the full ring specimen, but because of the difficulty in obtaining a satisfactory polish on many of these large specimens, smaller samples have been cut from the "A" ring of the same sectioned coupons and the photomicrographs taken of these (see Fig. 26 of reference 5). When examining these micrographs one should remember that the features shown may not be "typical" of the relevant quadrant of the specimen, but rather represent the area of maximum attack, or the most interesting form of attack.

All measurements in the data sheets are in μm. A negative metal loss figure indicates an apparent growth of the alloy. Two dashes "--" are used for "0", and "TR" for "trace", generally less than 7 μm.

Metal Loss: The metal loss is defined as the difference between the original thickness and the remaining metal thickness after exposure. Remaining metal thickness includes any internally attacked metal. The thickness after exposure is the minimum thickness at, or close to, the 8 "positions". For some coupons/positions, the metal loss was determined by measuring the surface profile within one field of view at a magnification of about 500X. This was done when measurement of the remaining metal gave a larger value than the original thickness.

Internal Penetration: (Internal Pen. or Internal Attack) The internal penetration is defined as the maximum depth of penetration or precipitation of oxides or sulphides, with the outer boundary being the same as that which defines the minimum thickness of the remaining metal as discussed above. The inner boundary can be difficult to determine, especially if there is precipitation of fine sulphides. Most of the samples have been examined unetched (at present) and thus, phases having a metallic appearance (eg. carbides) are probably not included. Phases believed to be precipitated from the alloy only as a result of the thermal exposure (eg. sigma phase) have not been included.

Scale: The scale is the nominal thickness of what appears to be the corrosion product on the surface of the alloy.

Deposit: The deposit is the nominal thickness of what appears to be a deposit composed primarily of bed material on top of the scale. Some coupons have several layers of "deposit", and some of this may actually be a corrosion product scale, or an intermediate layer formed as the result of a reaction between the deposit and scale. However, at the present time this is included with the "deposit".

Bore Scale: The bore scale is the thickness of the scale formed on the bore (air side) of the coupon. Although the thickness of this scale on the austenitic alloys was recorded when it was sufficiently thick to measure, the measurements of the remaining metal (used to calculate metal loss) were taken at locations where the bore scale was negligible, or where it was possible to determine the position of the surface of the alloy. Generally, the bore scale on the austenitic alloys is not a continuous scale, but rather exists as discrete islands of scale on the alloy.

The numerical thickness values given in the data sheets and tables should not be considered absolute. The original thicknesses of the coupons were measured with a micrometer and thus, may have an error of at least 5 μm. Non-perpendicularity of the mounted section can lead to additional errors of up to perhaps 10 μm on the ring sections, and greater than this on the welded sections. Thus the measurements of the metal loss are probably accurate to +-10 μm. Depth of internal penetration is more dependent on the judgement of the observer, but this is not a critical point for most alloys. The type of attack is perhaps more important than the depth of attack to the nearest few microns.

Measurements of the thickness of scale, deposit and bore scale are generally accurate to 5 μm. Wherever possible, these measurements were made at locations where the scales/deposits were microscopically uniform. However, it is obvious that on many coupons spalling of deposit and/or scale has taken place many times during the exposure and thus, the significance of the measurements is questionable.

The hardness measurements have been made on the sectioned surface of the "C" ring section with a standard Rockwell hardness tester.

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Table 1: Temperature data from the thermocouples in probe 2B2, degrees Celsius. NSPC data.

TC	COUPON	RUN 5	6	7	8	9	AVERAGE
1	3T	645	640	638	634	635	638
2	3B	560	559	576	569	566	566
3	8T	680	683	678	673	672	677
4	8B	627	624	638	629	628	629
5	13T	696	700	701	701	701	700
6	13B	675	671	673	673	668	672
7	18T	698	700	699	699	700	699
8	18B	696	691	692	689	686	691

Table 2: Temperature data from the thermocouples in probe 4B1, degrees Celsius. NSPC data.

TC	COUPON	RUN 2	3	4	5	6	7	8	9	AVERAGE
1	3T	647	633	630	618	601	591	626	624	621
2	3B	553	543	537	537	511	491	546	552	534
3	8T	655	637	635	621	592	587	625	629	622
4	8B	642	628	623	625	594	567	608	612	612
5	13T	678	670	668	655	630	629	667	666	658
6	13B	697	693	686	686	---	642	---	---	685
7	18T	693	684	679	673	660	649	686	687	677
8	18B	699	699	697	698	680	665	695	699	691

Table 3: Estimated coupon top and bottom temperatures for probe 2B2, degrees Celsius.

COUPON	TOP	BOTTOM
1	622	541
2	630	553
3 *	638	566
4	646	579
5	654	591
6	661	604
7	669	616
8 *	677	629
9	682	638
10	686	646
11	691	655
12	695	663
13 *	700	672
14	700	676
15	700	680
16	699	683
17	699	687
18 *	699	691
19	699	695
20	699	699

* Contains thermocouples - temperatures from Table 1.
All other figures are derived from linear interpolation or extrapolation based on the thermocouple data.

Table 4: Estimated coupon top and bottom temperatures for probe 4B1, degrees Celsius.

COUPON		TOP	BOTTOM
1		621	503
2		621	518
3	*	621	534
4		621	550
5		621	565
6		622	581
7		622	596
8	*	622	612
9		629	627
10		636	641
11		644	656
12		651	670
13	*	658	685
14		662	686
15		666	687
16		669	689
17		673	690
18	*	677	691
19		681	692
20		685	693

* Contains thermocouples - temperatures from Table 2.
All other figures are derived from linear interpolation or extrapolation based on the thermocouple data.

Table 5: Joints in probes 2B2, 4B1 and 9DL3 that unscrewed.

Probe 2B2

Inlet/1

Probe 4B1

Inlet/1 2/3 8/9 11/12 12/13
15/16 19/20

Probe 9DL3

1/2* 14/15 18/19 19/20

* Separated on removal from combustor.

Table 6. Metal loss (μm) of probe 2B2.

		POSITION							
COUPON		1	2	3	4	5	6	7	8
1	W N82	10	5	165			40	70	100
2	T91	160	150	130	125	155	185	95	225
3	304H	20	20	30	60	90	35	30	5
4	347H	30	40	35	55	90	75	40	35
5	310	10	20	20	50	75	35	15	0
6	800H	10	10	45	90	100	15	10	15
7	W N82	0	0	85			30	45	135
8	T91	120	155	150	250	210	155	170	60
9	304H	50	40	40	50	60	50	60	45
10	347H	10	50	30	20	45	60	30	40
11	310	50	20	15	20	15	15	10	35
12	800H	25	15	15	15	0	10	15	20
13	304H	50	30	25	35	60	60	30	25
14	347H	105	30	45	25	35	40	40	40
15	310	50	50	30	25	35	25	10	15
16	800H	35	5	10	20	15	35	20	20
17	304H	20	30	30	60	115	75	35	25
18	347H	35	35	20	50	95	35	20	25
19	310	10	5	15	25	20	15	10	0
20	800H	15	10	20	25	15	10	10	10

Note: Coupons 1 and 7: 1/304H, 2/N82, 3/T91 at position 4, bottom.
6/304H, 7/N82, 8/T91 at position 8, top.

Table 7. Internal attack (μm) of probe 2B2.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	W N82	TR	0	10			TR	0	TR
2	T91	15	TR	10	TR	TR	15	35	TR
3	304H	20	20	TR	TR	15	25	40	25
4	347H	35	15	15	15	15	45	25	20
5	310	60	55	25	20	15	75	55	70
6	800H	90	65	30	20	55	45	70	30
7	W N82	20	15	20			TR	TR	0
8	T91	0	0	0	TR	0	0	15	0
9	304H	55	45	15	30	30	80	45	45
10	347H	35	35	30	30	25	35	45	30
11	310	85	60	60	30	55	100	80	45
12	800H	40	85	90	55	140	40	50	95
13	304H	55	60	50	20	20	80	70	45
14	347H	85	40	25	20	40	50	40	55
15	310	75	80	70	100	100	95	80	65
16	800H	90	25	10	90	135	95	115	105
17	304H	45	40	55	50	60	50	55	35
18	347H	25	30	35	15	25	35	40	20
19	310	40	55	25	40	60	70	70	60
20	800H	65	35	25	35	40	85	85	25

Note: Coupons 1 and 7: 1/304H, 2/N82, 3/T91 at position 4, bottom.
6/304H, 7/N82, 8/T91 at position 8, top.

Table 8. Total attack (μm) of probe 2B2.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	W N82	10	5	117			40	70	82
2	T91	125	112	110	95	117	157	82	177
3	304H	40	40	30	60	105	60	70	30
4	347H	65	55	50	70	105	120	65	55
5	310	70	75	45	70	90	110	70	70
6	800H	100	75	75	110	155	60	80	45
7	W N82	20	15	32			30	45	107
8	T91	87	87	77	200	177	130	145	35
9	304H	105	85	55	80	90	130	105	90
10	347H	45	85	60	50	70	95	75	70
11	310	135	80	75	50	70	115	90	80
12	800H	65	100	105	70	140	50	65	115
13	304H	105	90	75	55	80	140	100	70
14	347H	190	70	70	45	75	90	80	95
15	310	125	130	100	125	135	120	90	80
16	800H	125	30	20	110	150	130	135	125
17	304H	65	70	85	110	175	125	90	60
18	347H	60	65	55	65	120	70	60	45
19	310	50	60	40	65	80	85	80	60
20	800H	80	45	45	60	50	50	95	35

Note: Coupons 1 and 7: 1/304H, 2/N82, 3/T91 at position 4, bottom.
6/304H, 7/N82, 8/T91 at position 8, top.

Table 9. Metal loss (μm) of probe 4B1.

		POSITION							
COUPON		1	2	3	4	5	6	7	8
1	W N82	860	795	660			10	30	160
2	T91	180	170	165	170	190	115	205	165
3	304H	35	35	95	230	210	35	30	35
4	347H	50	45	75	300	285	40	25	35
5	310	10	15	60	350	420	20	5	0
6	800H	25	415	470	370	30	25	5	20
7	W N82	370	950	555			5	110	155
8	T91	105	135	310	385	400	145	140	90
9	304H	45	50	150	320	305	35	20	45
10	347H	55	105	80	245	305	50	70	30
11	310	5	115	80	275	290	40	25	10
12	800H	15	35	105	260	240	40	10	15
13	304H	45	70	80	210	235	50	70	45
14	347H	70	215	130	190	155	45	15	20
15	310	55	60	125	175	125	35	25	25
16	800H	10	90	50	110	80	60	5	10
17	304H	60	100	60	130	150	85	50	40
18	347H	60	125	160	120	110	80	30	40
19	310	35	40	65	155	150	65	25	45
20	800H	115	120	55	185	140	75	50	85

Note: Coupons 1 and 7: 1/304H, 2/N82, 3/T91 at position 4, bottom.
6/304H, 7/N82, 8/T91 at position 8, top.

Table 10. Internal attack (μm) of probe 4B1.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	W N82	55	0	0			0	0	0
2	T91	TR	TR	10	TR	TR	TR	TR	TR
3	304H	25	15	TR	TR	TR	20	30	30
4	347H	20	35	30	TR	TR	35	30	15
5	310	25	40	45	TR	TR	35	30	20
6	800H	95	15	10	20	80	50	60	80
7	W N82	0	145	15			50	40	40
8	T91	15	15	10	TR	TR	10	15	15
9	304H	60	70	65	15	10	75	55	35
10	347H	40	45	30	30	20	30	30	35
11	310	70	70	125	25	20	105	25	45
12	800H	110	195	290	65	45	130	65	95
13	304H	45	65	75	45	30	55	80	45
14	347H	35	60	50	50	30	55	35	40
15	310	80	125	95	75	50	100	40	40
16	800H	80	285	275	175	70	125	110	85
17	304H	55	75	120	65	30	55	55	50
18	347H	50	80	45	45	40	70	35	30
19	310	65	75	150	75	15	85	10	30
20	800H	20	50	110	15	TR	50	25	10

Note: Coupons 1 and 7: 1/304H, 2/N82, 3/T91 at position 4, bottom.
6/304H, 7/N82, 8/T91 at position 8, top.

Table 11. Total attack (μm) of probe 4B1.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	W N82	915	795	651			10	30	132
2	T91	147	132	147	152	167	80	172	132
3	304H	60	50	95	230	210	55	60	65
4	347H	70	80	105	300	285	75	55	50
5	310	35	55	105	350	420	55	35	20
6	800H	120	430	480	390	110	75	65	100
7	W N82	370	1095	430			55	150	65
8	T91	80	90	270	335	342	102	110	60
9	304H	105	120	215	335	315	110	75	80
10	347H	95	150	110	275	325	80	100	65
11	310	75	185	205	300	310	145	50	55
12	800H	125	230	395	325	285	170	75	110
13	304H	90	135	155	255	265	105	150	90
14	347H	105	275	180	240	185	100	50	60
15	310	135	185	220	250	175	135	65	65
16	800H	90	375	325	285	150	185	115	95
17	304H	115	175	180	195	180	140	105	90
18	347H	110	205	205	165	150	150	65	70
19	310	100	115	215	230	165	150	35	75
20	800H	135	170	165	200	140	125	75	95

Note: Coupons 1 and 7: 1/304H, 2/N82, 3/T91 at position 4, bottom.
6/304H, 7/N82, 8/T91 at position 8, top.

Table 12. Metal loss (μm) of probe 9DL3.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	800H	20	3815	3865	2945	4185	90	20	25
2	347H	25	135	115	120	95	100	15	25
3	310	5	10	25	45	25	35	20	-10
4	HK40	20	160	35	30	175	85	40	-10
5	253MA	5	70	70	75	20	100	35	45
6	800H	0	20	2490	1850	1995	15	5	19
7	347H	5	35	70	105	80	20	10	0
8	310	10	20	25	35	45	15	20	10
9	HK40	60	35	35	30	25	55	35	0
10	253MA	55	60	70	20	105	95	150	130
11	800H	85	5	40	50	120	40	110	10
12	347H	5	5	16	30	35	50	10	20
13	310	15	5	0	25	35	65	70	10
14	HK40	15	0	40	30	15	45	55	100
15	253MA	105	95	160	155	115	130	130	60
16	800H	15	20	25	80	90	95	115	15
17	347H	15	15	40	20	25	10	5	0
18	310	0	15	25	25	20	15	10	5
19	HK40	10	25	80	115	120	80	35	10
20	253MA	70	210	310	255	310	305	220	15

Table 13. Internal attack (μm) of probe 9DL3.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	800H	230	1180	720	795	625	200	175	160
2	347H	45	110	95	105	100	70	40	30
3	310	55	65	110	100	70	80	55	35
4	HK40	165	220	190	205	230	250	175	130
5	253MA	80	85	85	55	45	85	95	75
6	800H	185	170	475	490	525	120	135	190
7	347H	30	35	90	115	75	45	25	25
8	310	50	95	55	50	50	40	45	40
9	HK40	180	185	110	60	50	210	205	100
10	253MA	130	160	150	65	120	145	140	150
11	800H	385	290	280	135	365	310	360	265
12	347H	25	30	35	35	30	30	25	30
13	310	45	135	45	40	160	175	180	45
14	HK40	90	165	255	170	230	250	205	215
15	253MA	165	145	175	165	180	180	170	145
16	800H	355	395	315	365	370	315	330	180
17	347H	50	25	25	25	30	35	40	60
18	310	90	105	65	40	40	175	100	80
19	HK40	125	365	285	95	130	190	230	115
20	253MA	85	190	75	110	115	150	150	125

Table 14. Total attack (μm) of probe 9DL3.

COUPON		POSITION 1	2	3	4	5	6	7	8
1	800H	250	4995	4585	3740	4810	290	195	185
2	347H	70	245	210	225	195	170	55	55
3	310	60	75	135	145	95	115	75	35
4	HK40	185	380	225	235	405	335	215	130
5	253MA	85	155	155	130	65	185	130	120
6	800H	185	190	2965	2340	2520	135	140	200
7	347H	35	70	160	220	155	65	35	25
8	310	60	115	80	85	95	55	65	50
9	HK40	240	220	145	90	75	265	240	100
10	253MA	185	220	220	85	225	240	290	280
11	800H	470	295	320	185	485	350	470	275
12	347H	30	35	50	65	65	80	35	50
13	310	60	140	45	65	195	240	250	55
14	HK40	105	165	295	200	245	295	260	315
15	253MA	270	240	335	320	295	310	300	205
16	800H	370	415	340	445	460	410	445	195
17	347H	65	40	65	45	55	45	45	60
18	310	90	120	90	65	60	190	110	85
19	HK40	135	390	365	210	250	270	265	125
20	253MA	155	400	385	365	425	455	370	140

Table 15. Comparison of the average and maximumn total attack rates in µm/a of the coupons in probes 2B1 (3000 h), 2B2 (5000 h) and 4B1 (8000 h).

		2B1		2B2		4B1	
Alloy	C	avg	max	avg	max	avg	max
T91	2	359	619	212	310	154	188
	8	391	511	205	350	189	347
304H	3	169	204	94	184	112	252
	9	222	306	161	227	185	367
	13	178	219	156	245	169	290
	17	204	336	170	306	161	213
347H	4	216	277	127	210	139	328
	10	189	262	119	166	164	356
	14	222	438	156	333	163	301
	18	163	204	117	210	153	224
310	5	222	306	131	192	146	460
	11	219	292	150	236	180	339
	15	219	321	198	236	167	273
	19	245	394	113	149	147	252
800H	6	233	452	152	271	242	525
	12	248	321	154	245	234	432
	16	292	467	180	262	221	410
	20	128	248	99	166	151	219

Table 16. Average and maximum total attack rates in µm/a of the coupons in probes 9DL1 (1000 h), 9DL2 (3000 h) and 9DL3 (4000 h).

		9DL1		9DL2		9DL3	
Alloy	C	avg	max	avg	max	avg	max
800H	1	859	1227	309	496	6953	10000+
	6	1148	1797	330	447	1967	5456
	11	815	1402	610	794	780	1062
	16	710	1314	604	861	843	1008
347H	2	298	394	102	172	335	536
	7	639	1534	116	251	208	482
	12	464	876	78	125	111	175
	17	438	657	96	207	113	142
310	3	482	657	64	134	199	317
	8	359	482	105	163	164	252
	13	368	438	119	277	287	547
	18	403	569	134	341	221	416
HK40	4	885	1534	90	149	576	887
	9	639	788	111	172	347	580
	14	429	657	242	493	515	690
	19	525	876	584	1101	550	854
253MA	5	587	832	154	233	280	405
	10	719	1577	201	268	477	635
	15	596	1008	359	736	622	734
	20	683	1490	739	1036	736	997

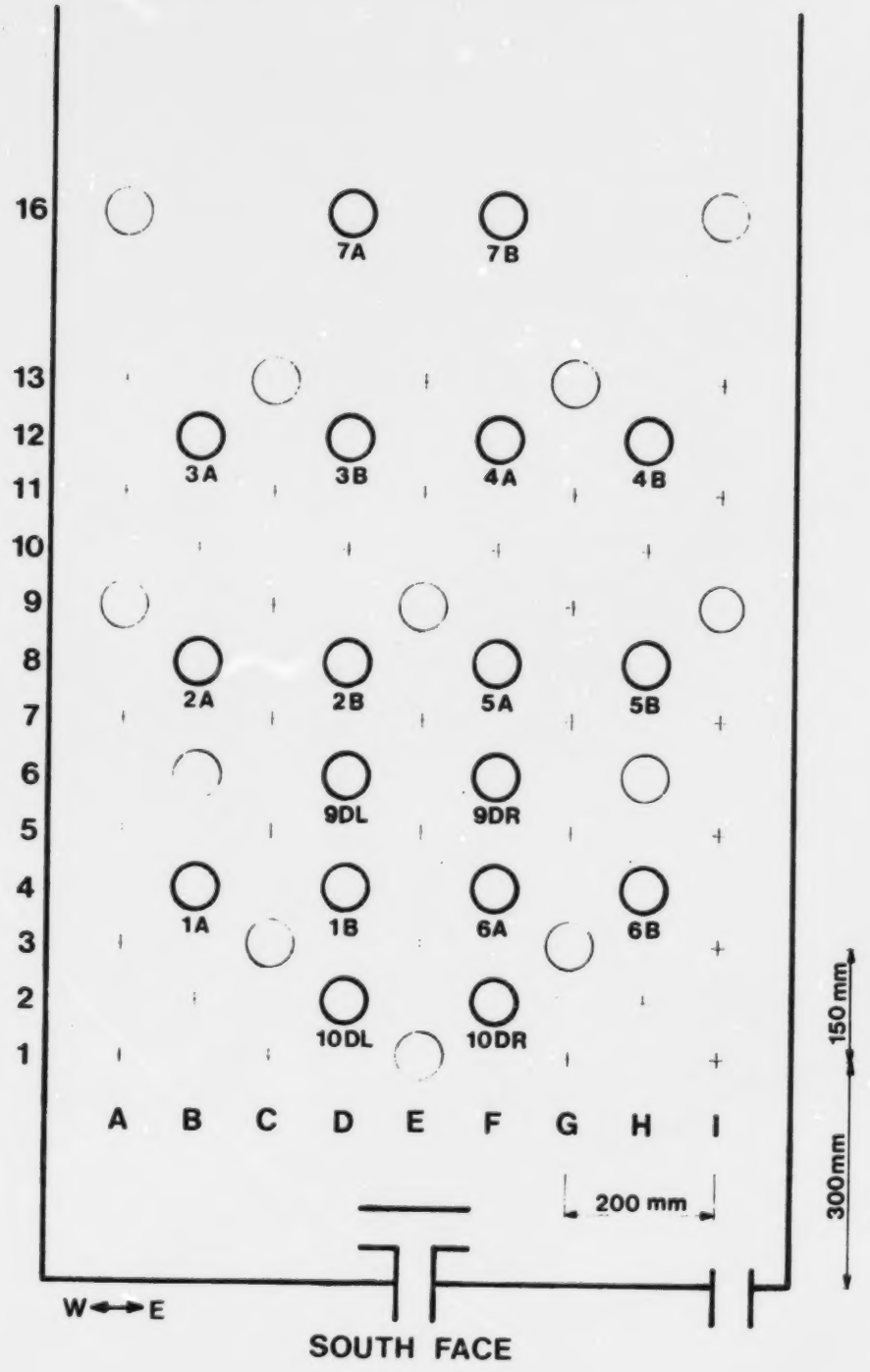


Fig. 1. South face of the combustor showing the locations of probes 2B2, 4B1 and 9DL3 and the oxygen probe ports (light circles).

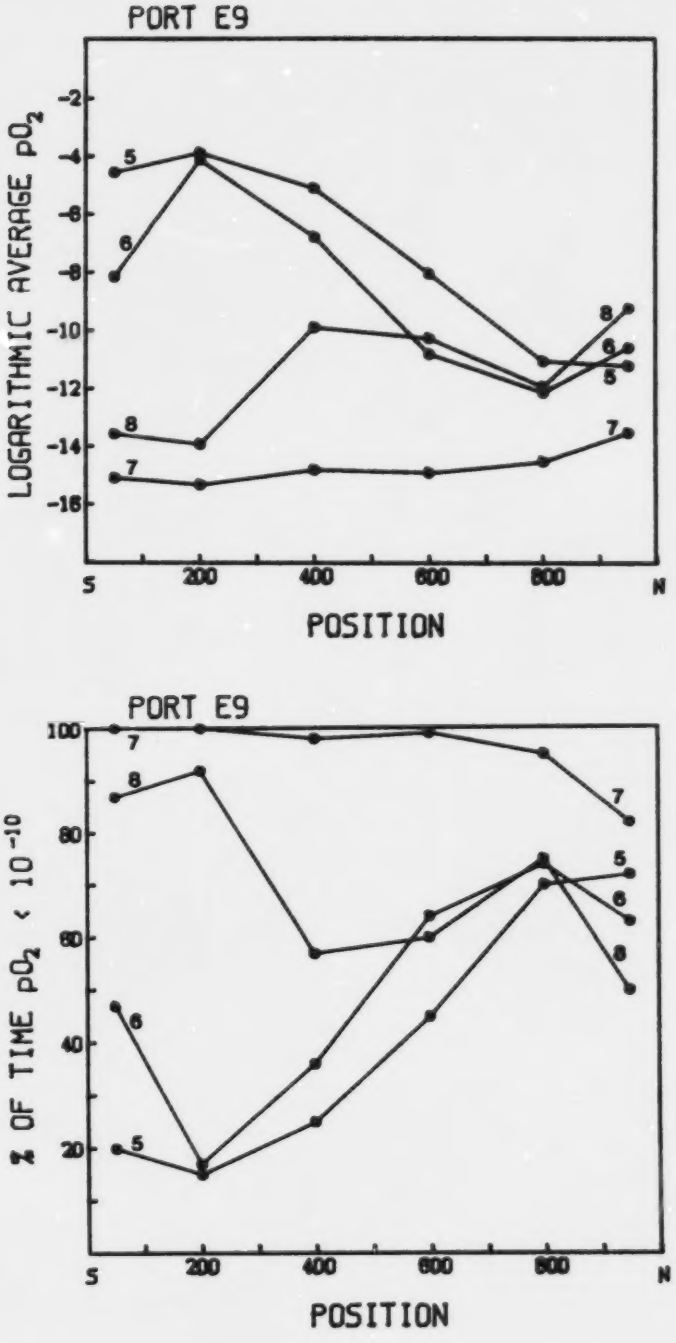


Fig. 2. Oxygen probe data from port E9 for runs 5 to 8.

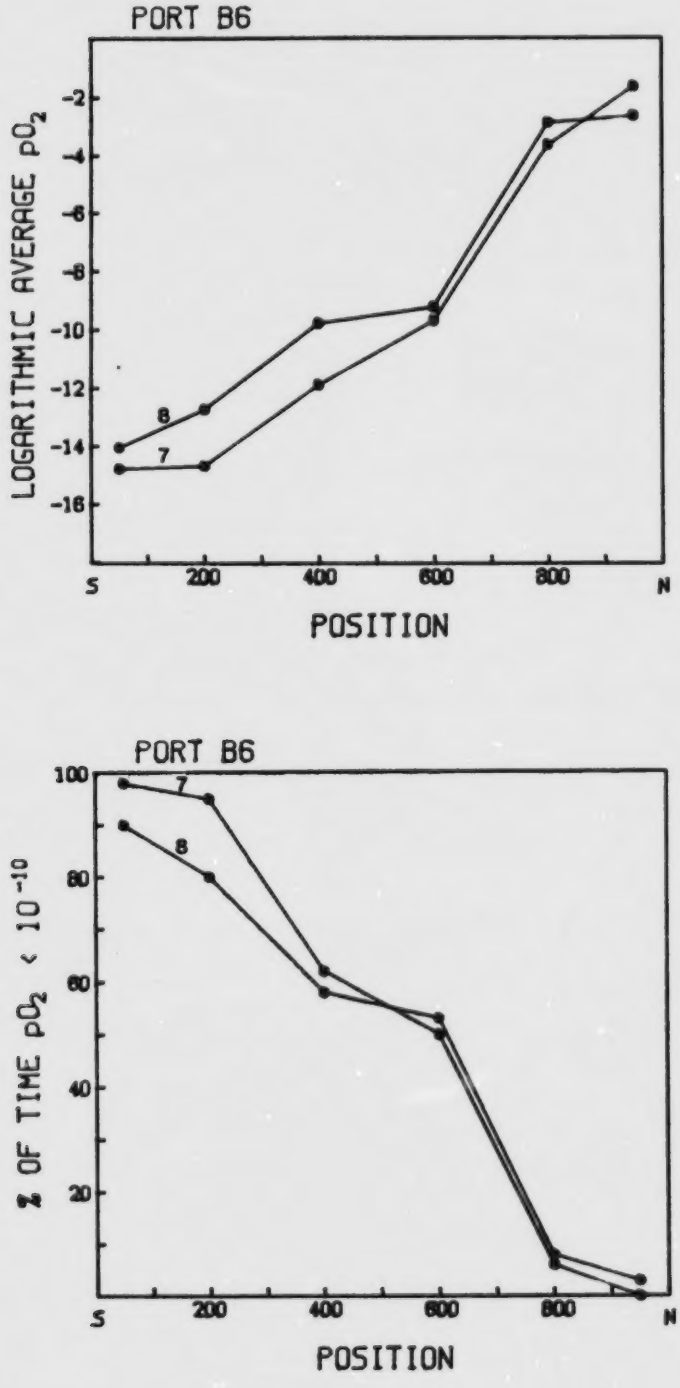


Fig. 3. Oxygen probe data from port B6 for runs 7 and 8.

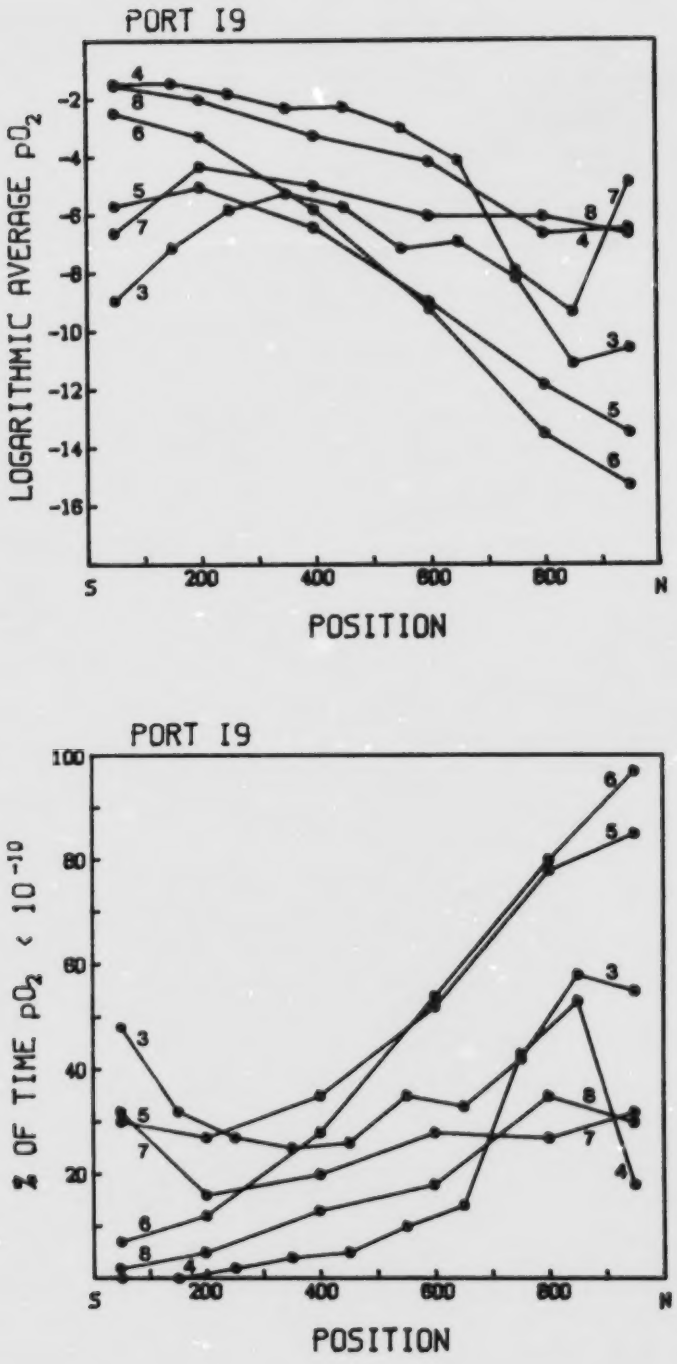
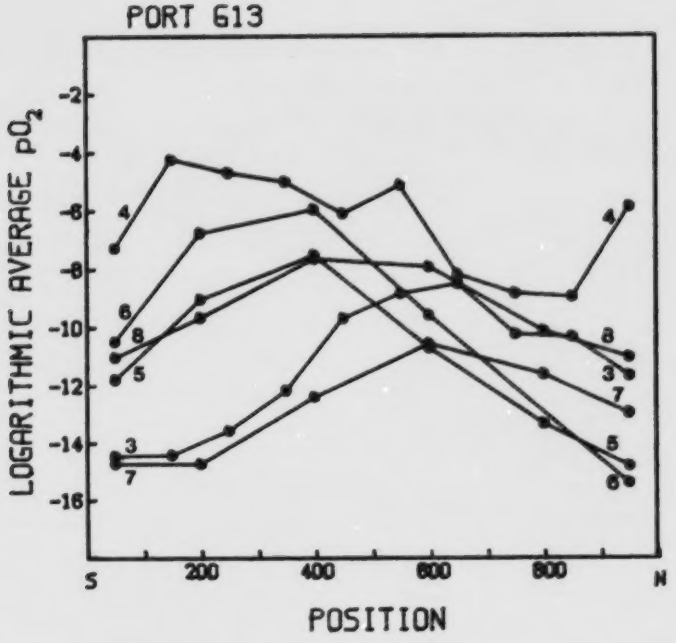


Fig. 4. Oxygen probe data from port I9 for runs 3 to 8.



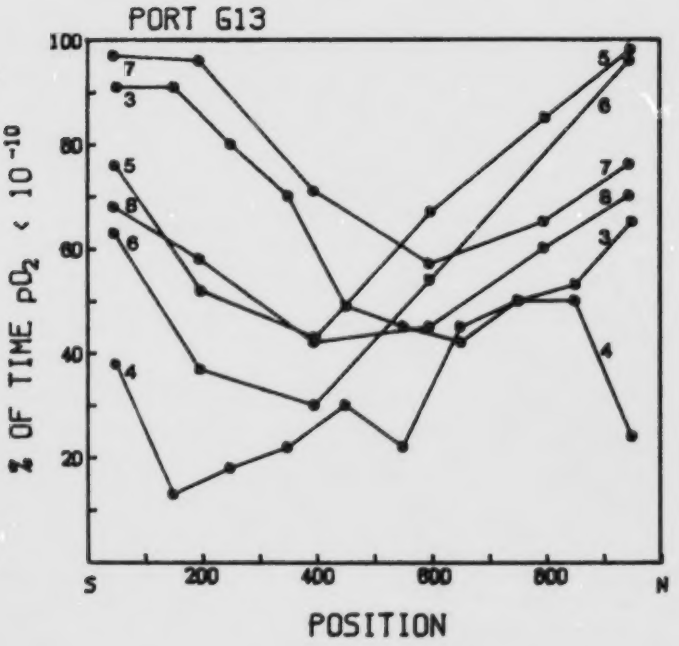


Fig. 5. Oxygen probe data from port G13 for runs 3 to 8.

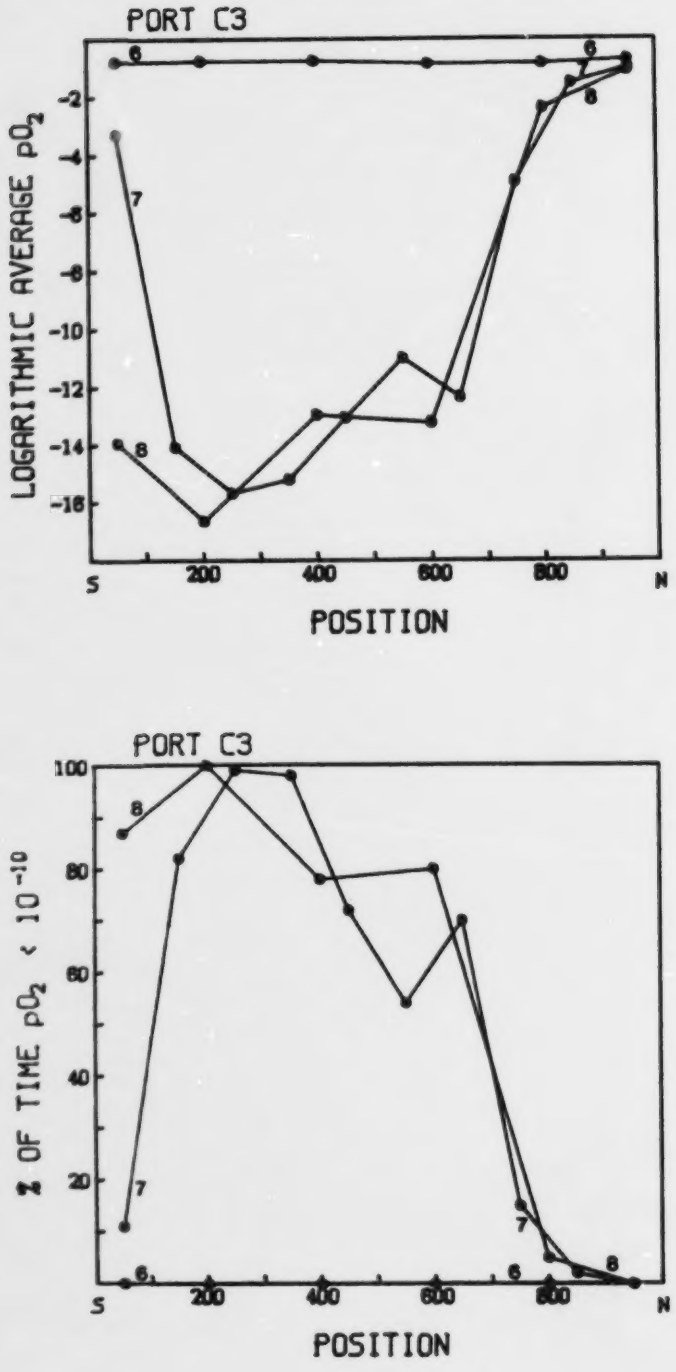


Fig. 6. Oxygen probe data from port C3 for runs 6 to 8.

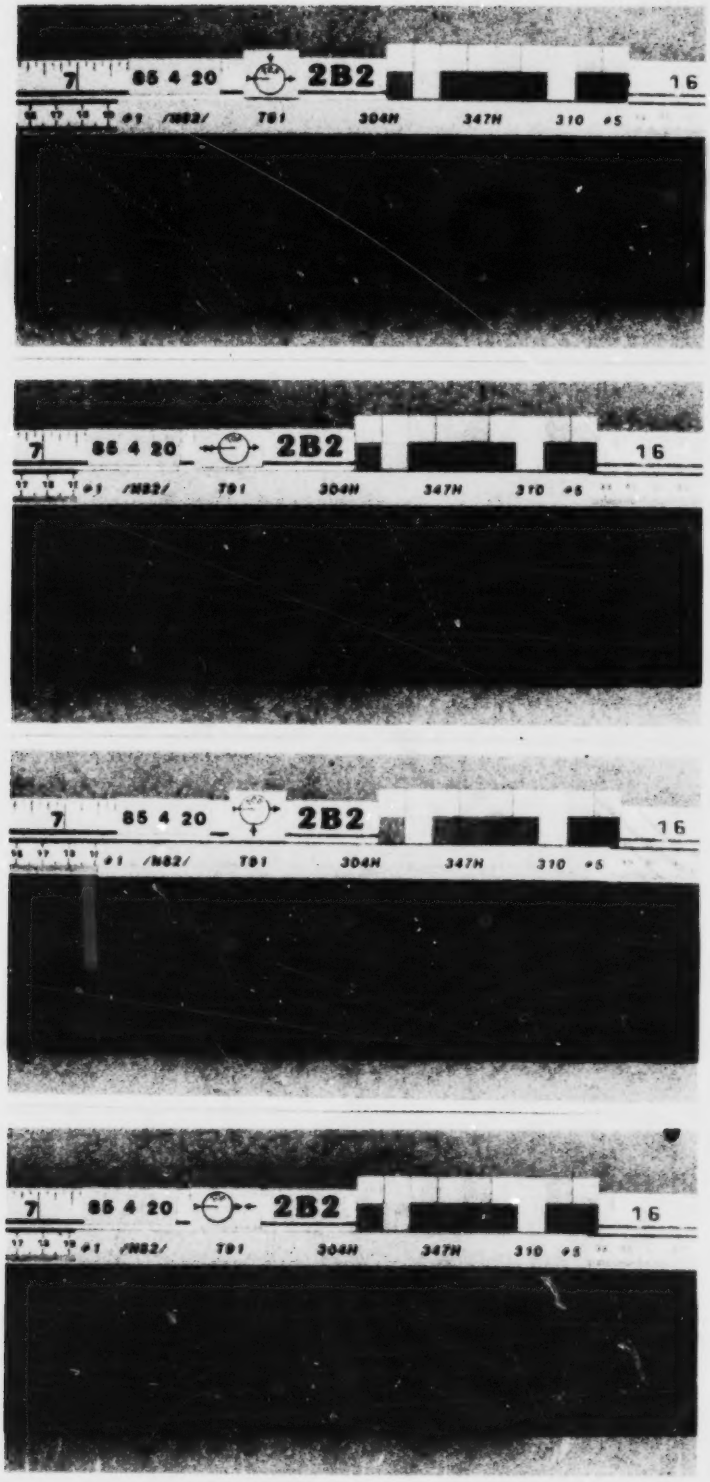


Fig. 7. Coupons 1 to 5 of probe 2B2.
1/W N82, 2/T91, 3/304H, 4/310, 5/800H.

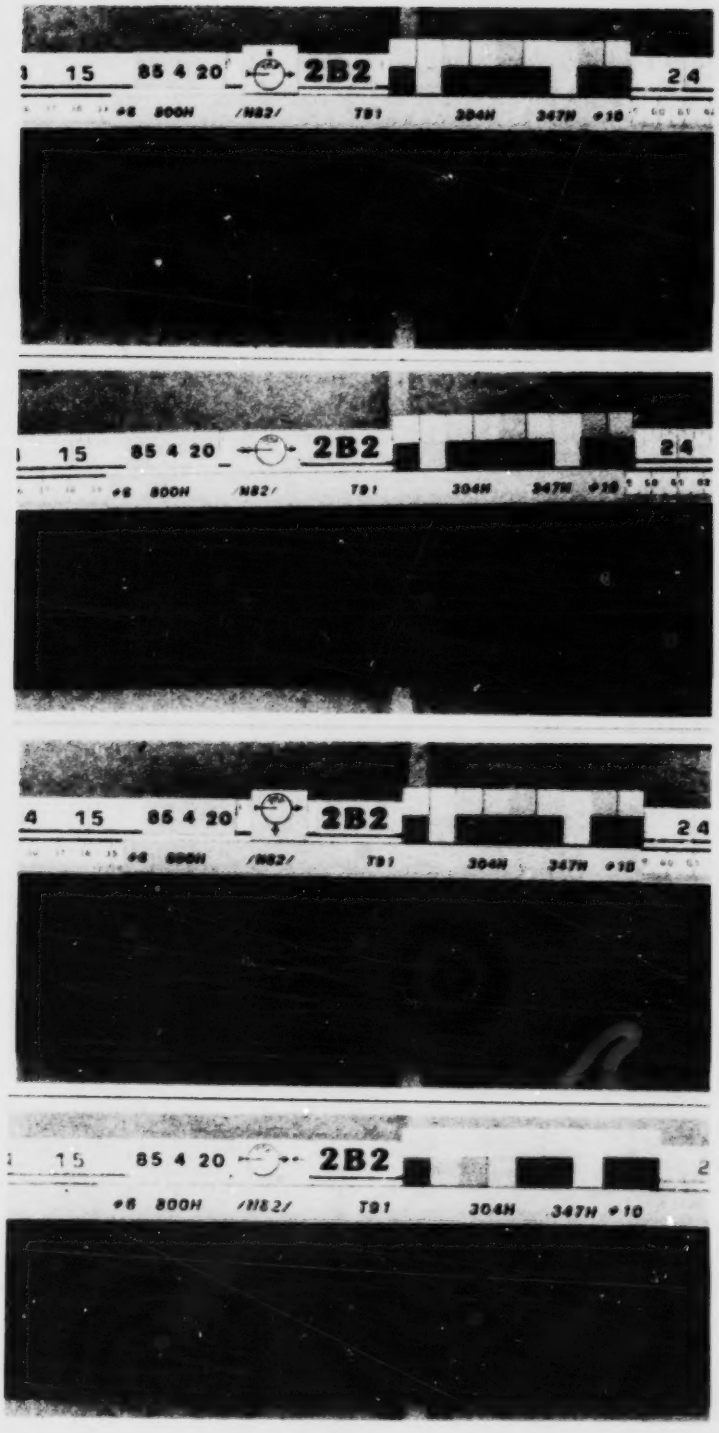


Fig. 8. Coupon 6 to 10 of probe 2B2.
6/800H, 7/W N82, 8/T91, 9/304H, 10/347H.

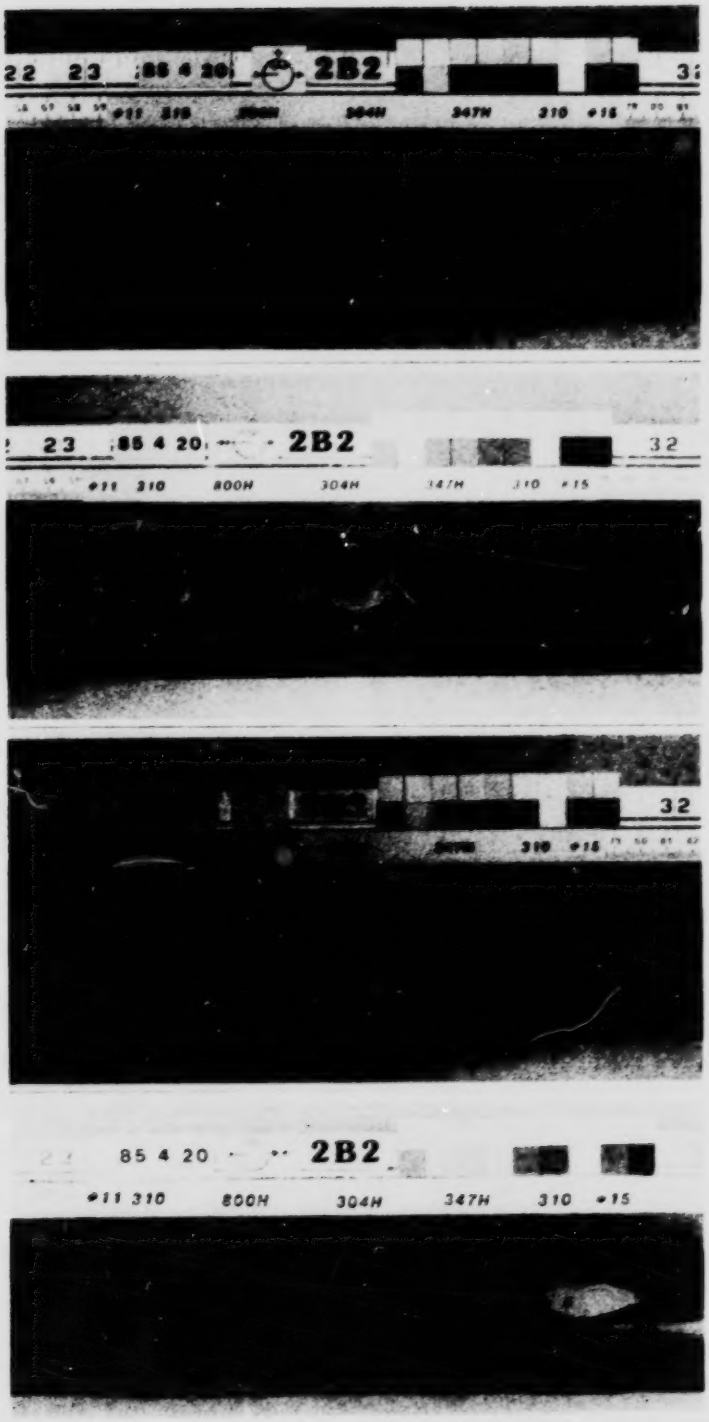


Fig. 9. Coupons 11 to 15 of probe 2B2.
11/310, 12/800H, 13/304H, 14/347H, 15/310.

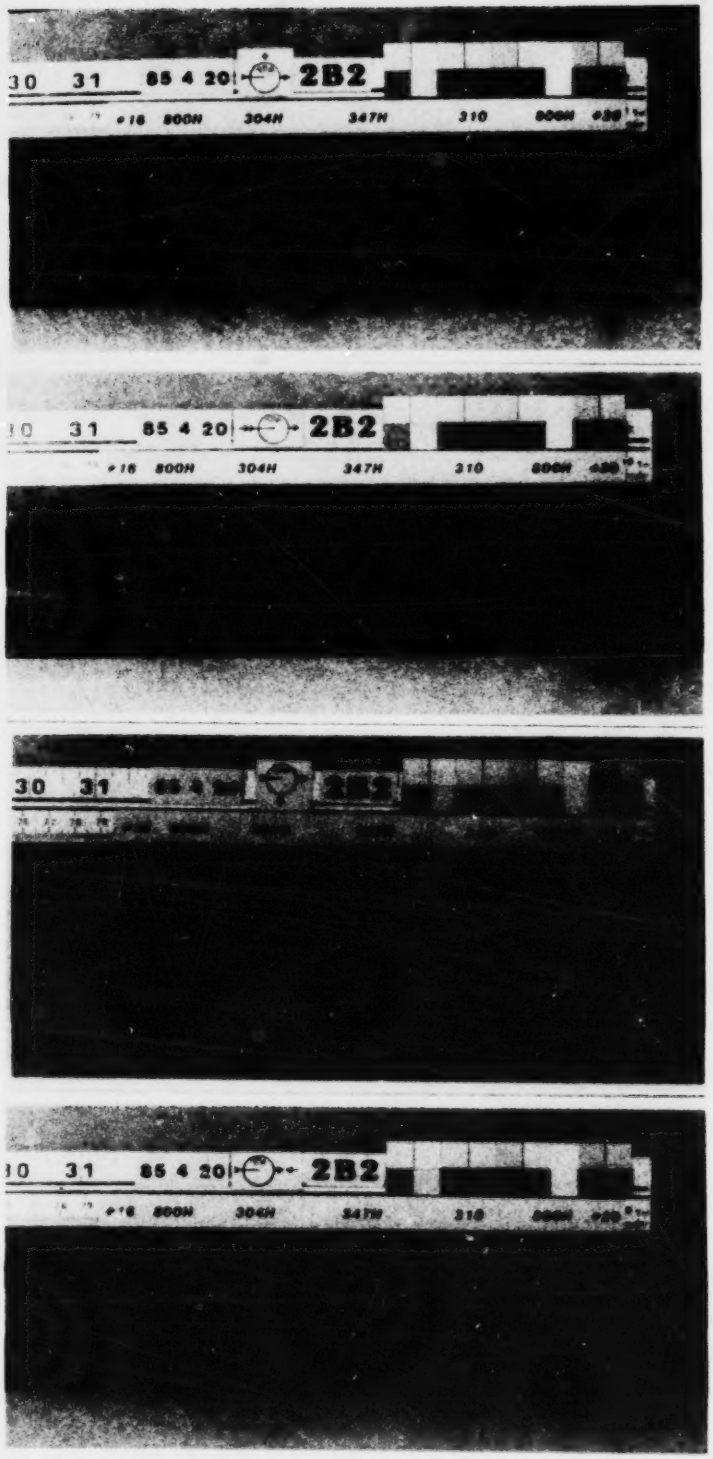


Fig. 10. Coupons 16 to 20 of probe 2B2.
16/800H, 17/304H, 18/347H, 19/310, 20/800H.

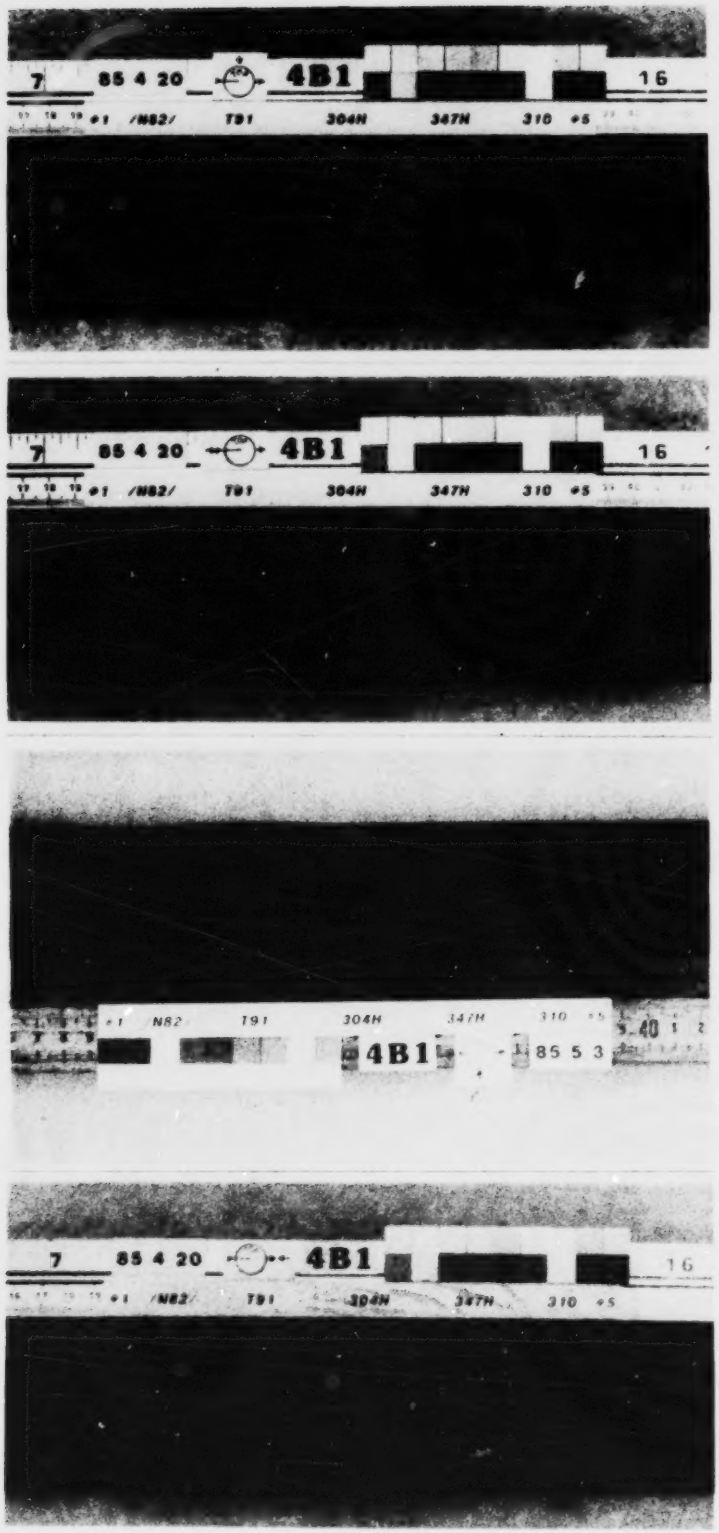


Fig. 11. Coupon 1 to 5 of probe 4B1.
1/W N82, 2/T91, 3/304H, 4/310, 5/800H.

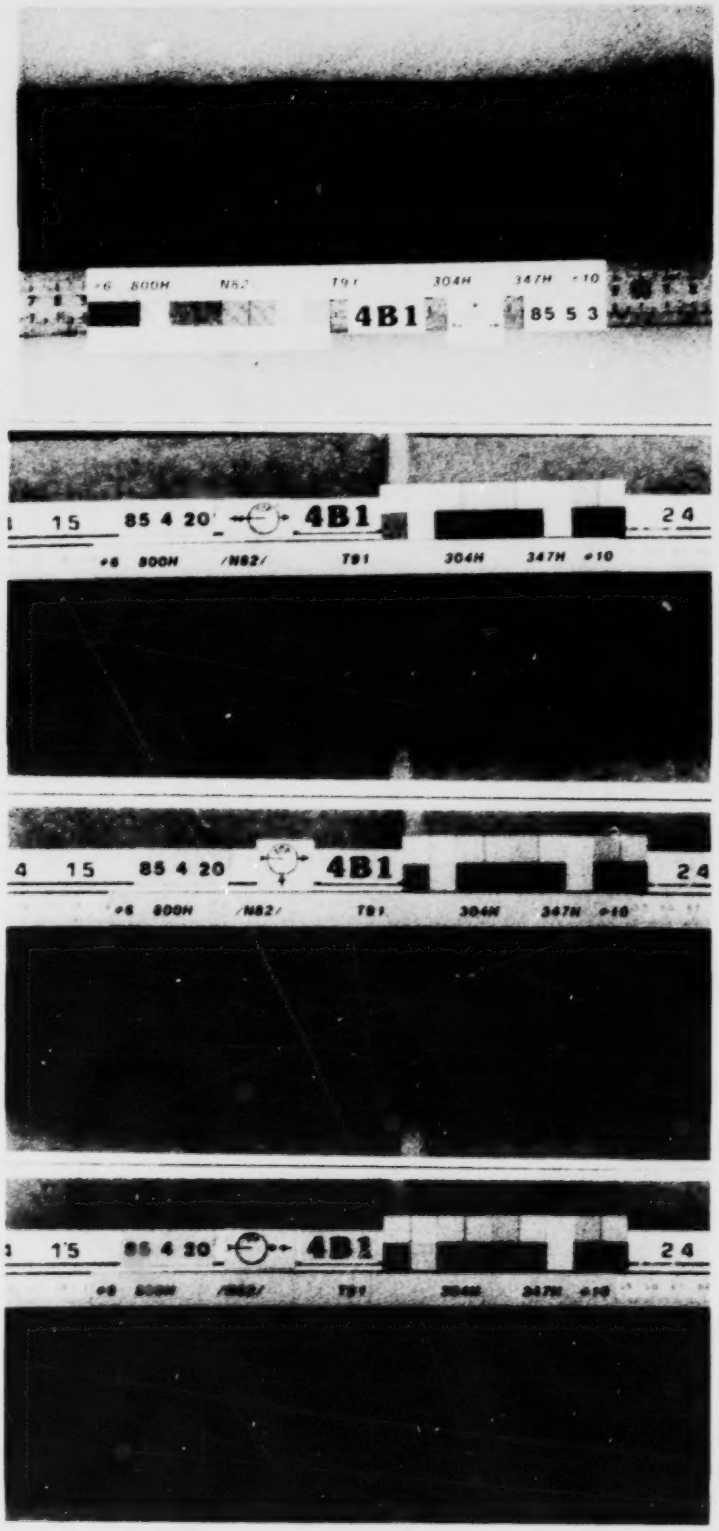


Fig. 12. Coupons 6 to 10 of probe 4B1.
6/800H, 7/W N82, 8/T91, 9/304H, 10/347H.

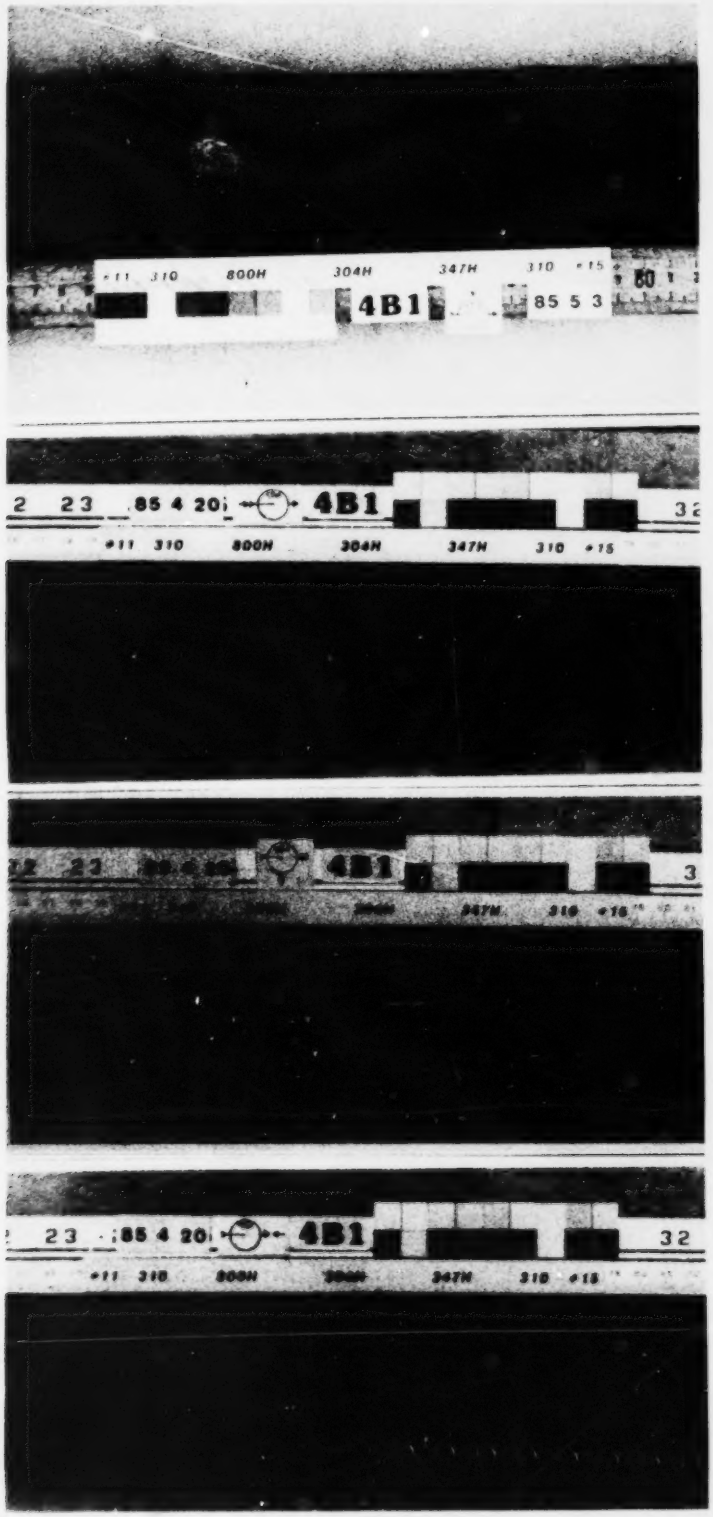


Fig. 13. Coupons 11 to 15 of probe 4B1.
11/310, 12/800H, 13/304H, 14/347H, 15/310.

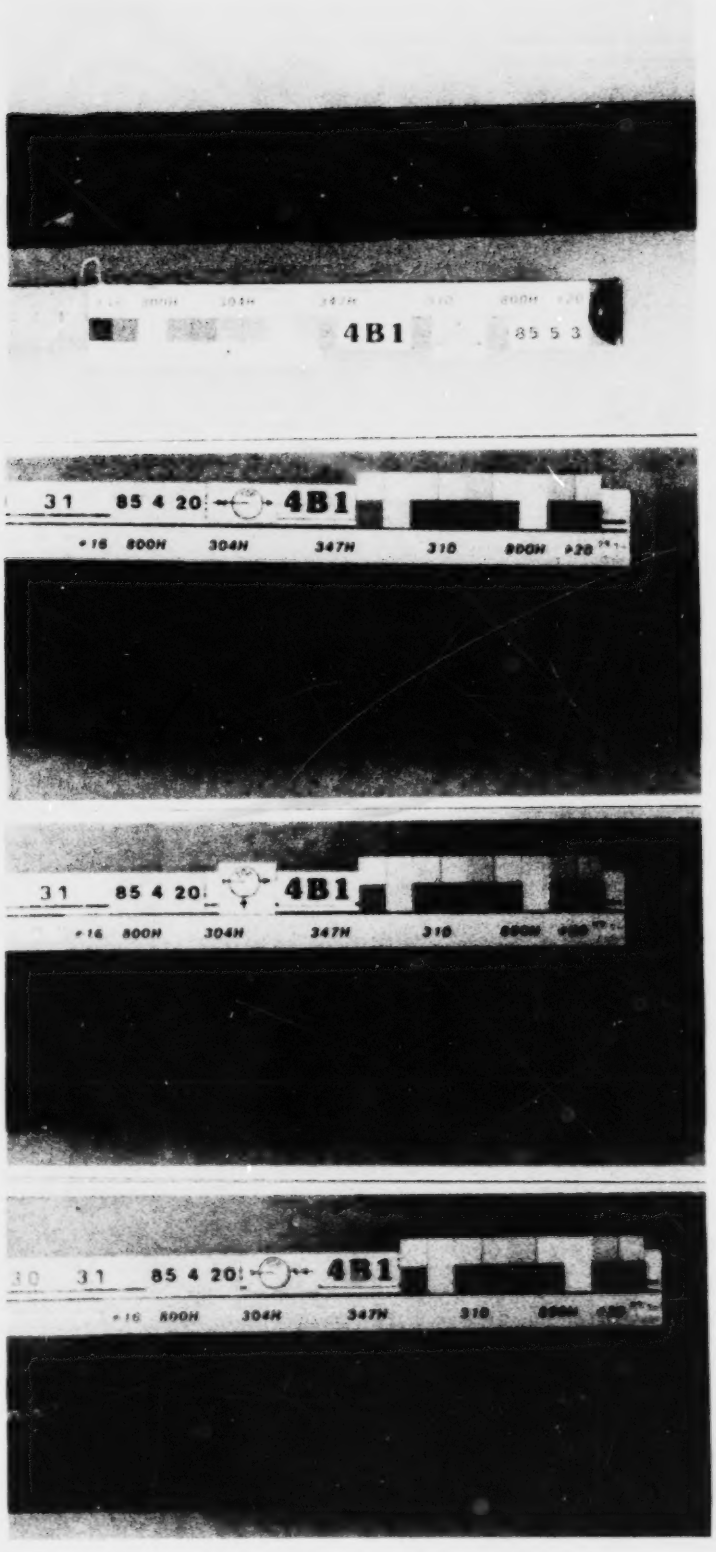


Fig. 14. Coupons 16 to 20 of probe 4B1.
16/800H, 17/304H, 18/347H, 19/310, 20/800H.

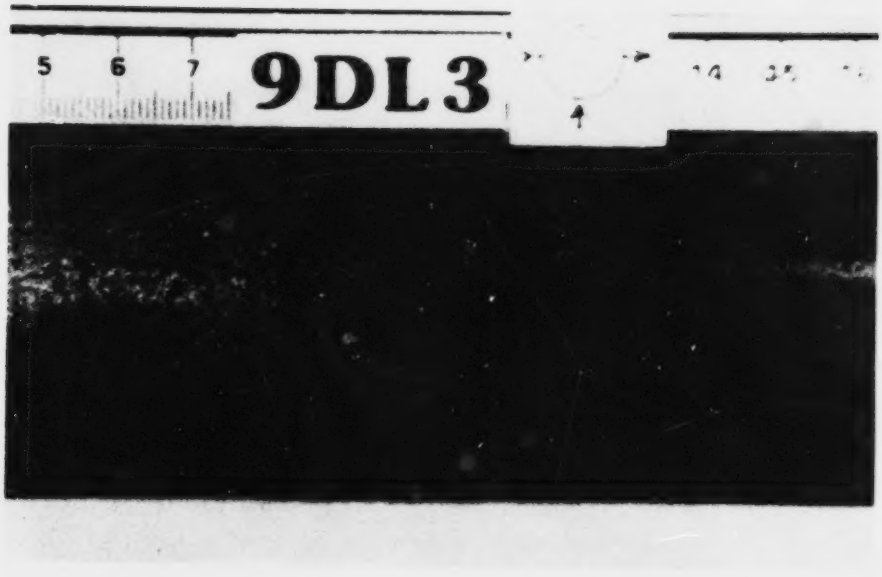


Fig. 15. Coupon 1 of probe 9DL3 at the end of run 8, bottom view.

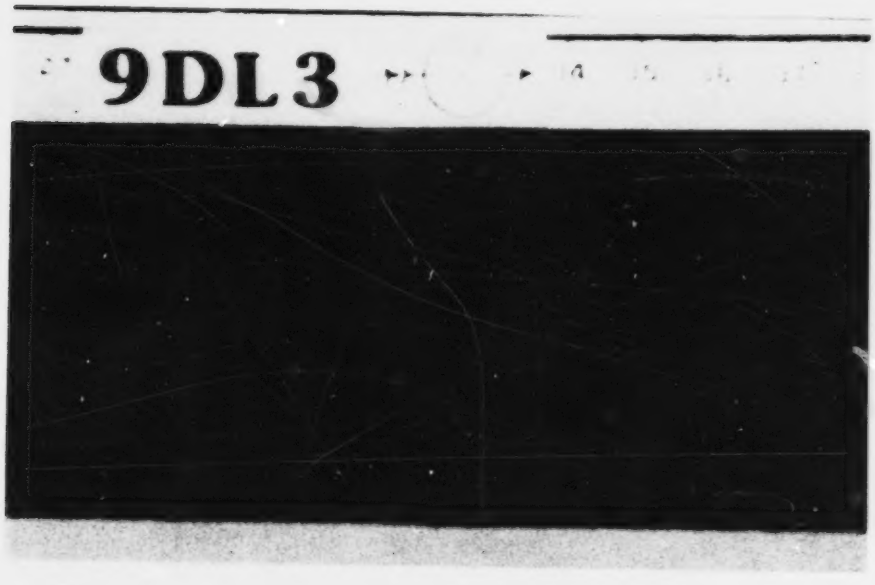


Fig. 16. Coupon 6 of probe 9DL3 at the end of run 8, side view.

Fig. 17. Coupon 1 of probe 9DL3 at the end of run 9, side view.

Fig. 18. Coupon 1 of probe 9DL3 at the end of run 9, bottom view

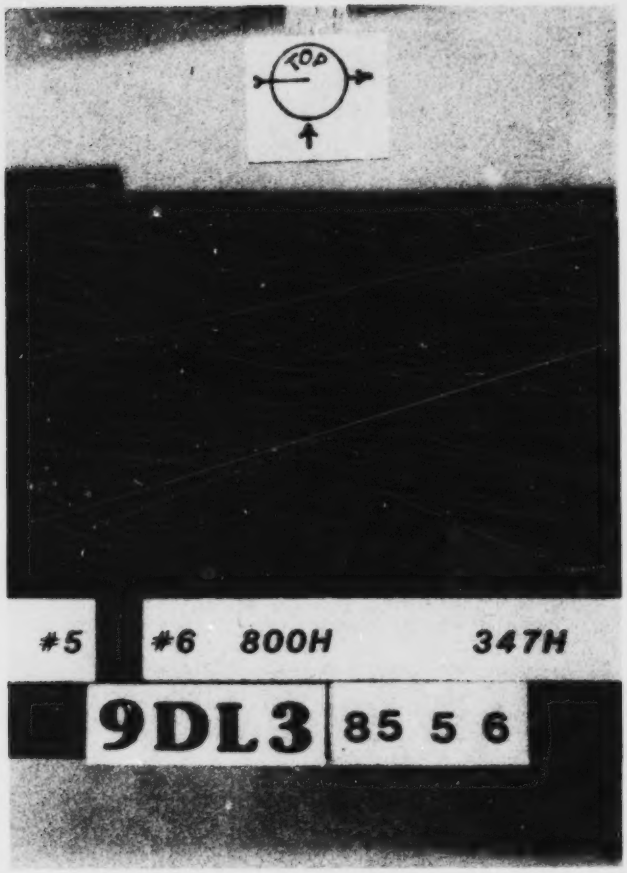


Fig. 19. Coupon 6 of probe 9DL3 at the end of run 9, bottom view.

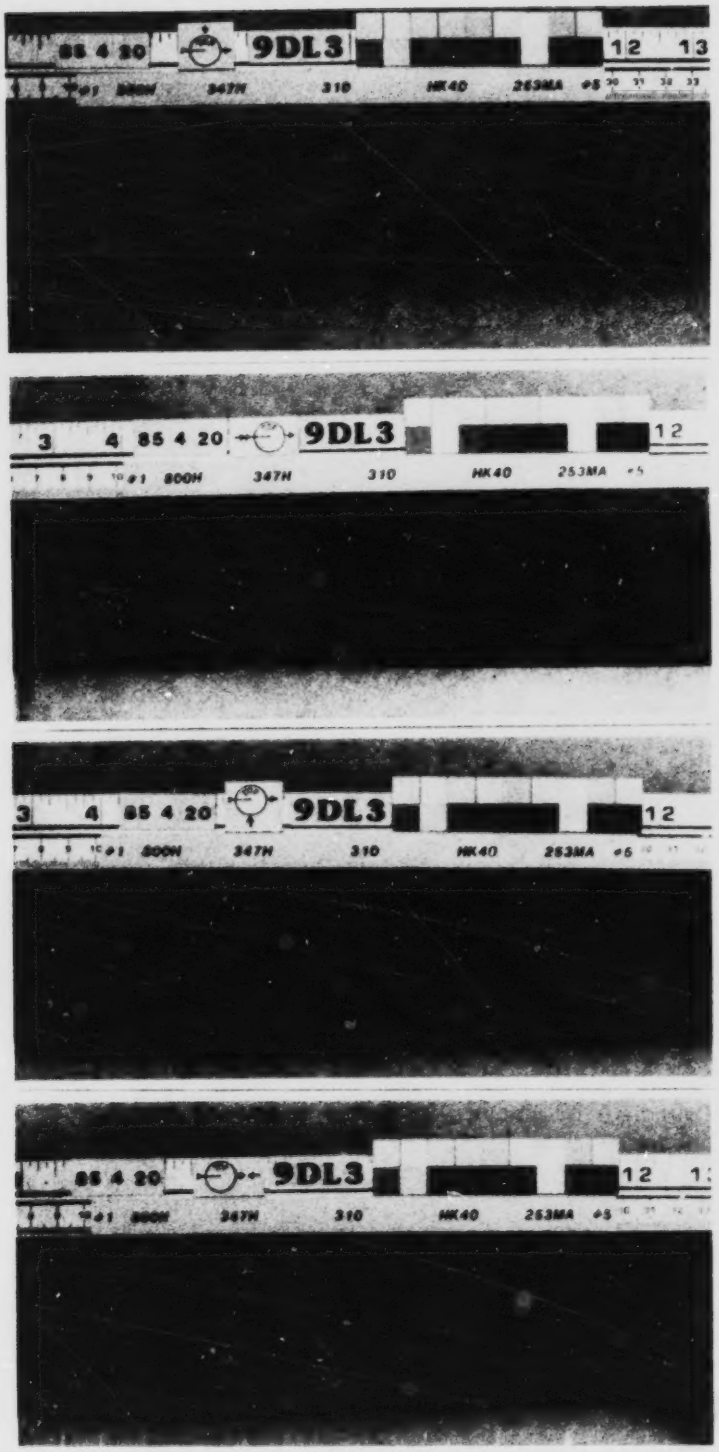


Fig. 20. Coupons 1 to 5 of probe 9DL3.
1/800H, 2/347H, 3/310, 4/HK40, 5/253MA.

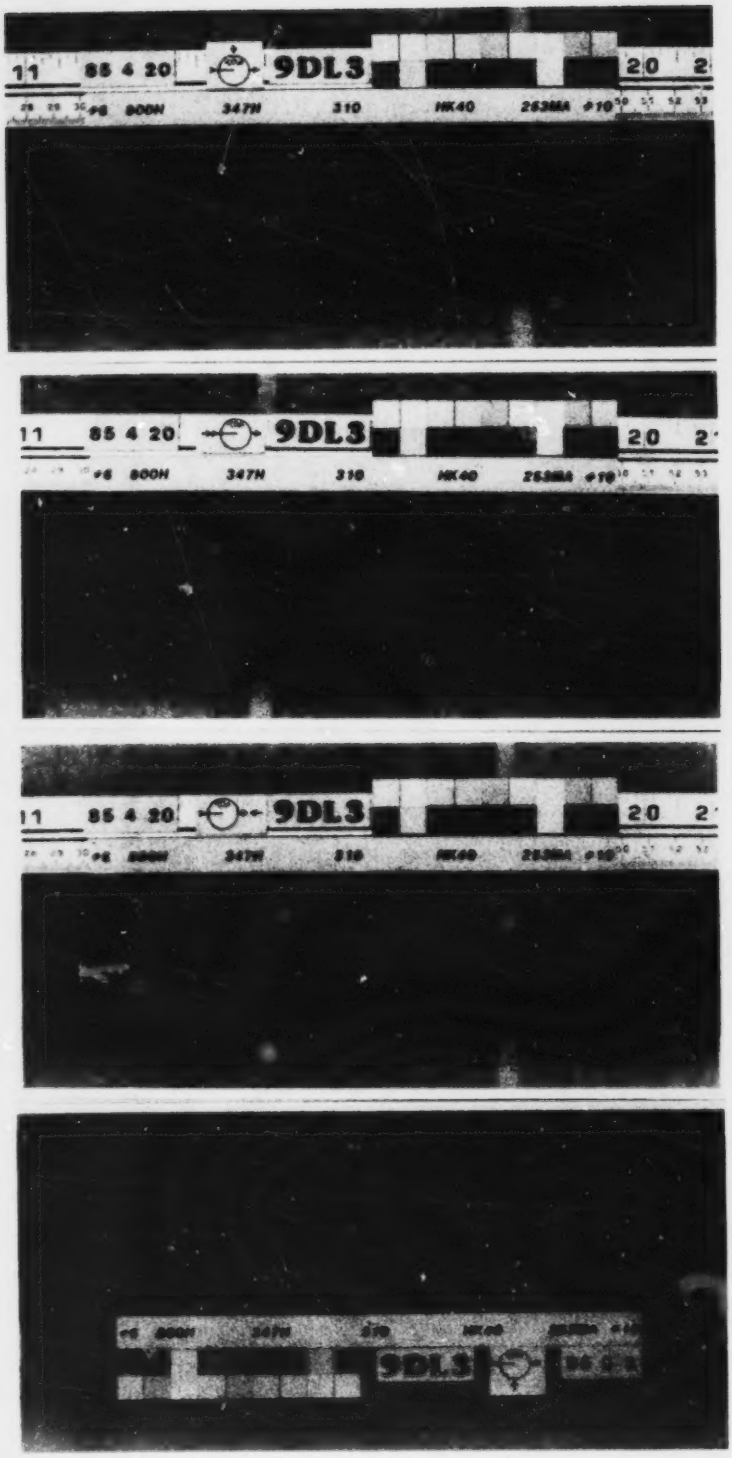


Fig. 21. Coupon 6 to 10 of probe 9DL3.
6/800H, 7/347H, 8/310, 9/HK40, 10/253MA.

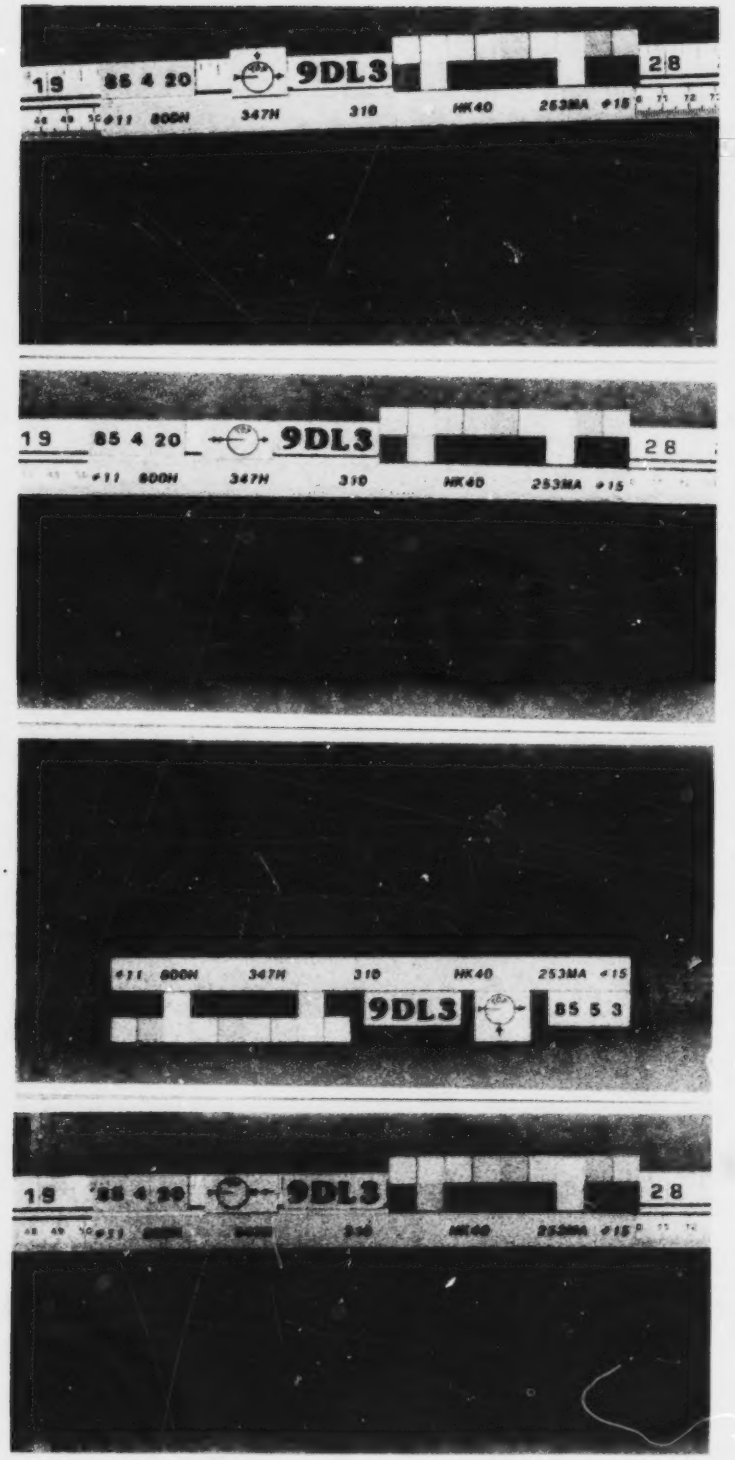


Fig. 22. Coupon 11 to 15 of probe 9DL3.
11/800H, 12/347H, 13/310, 14/HK40, 15/253MA.

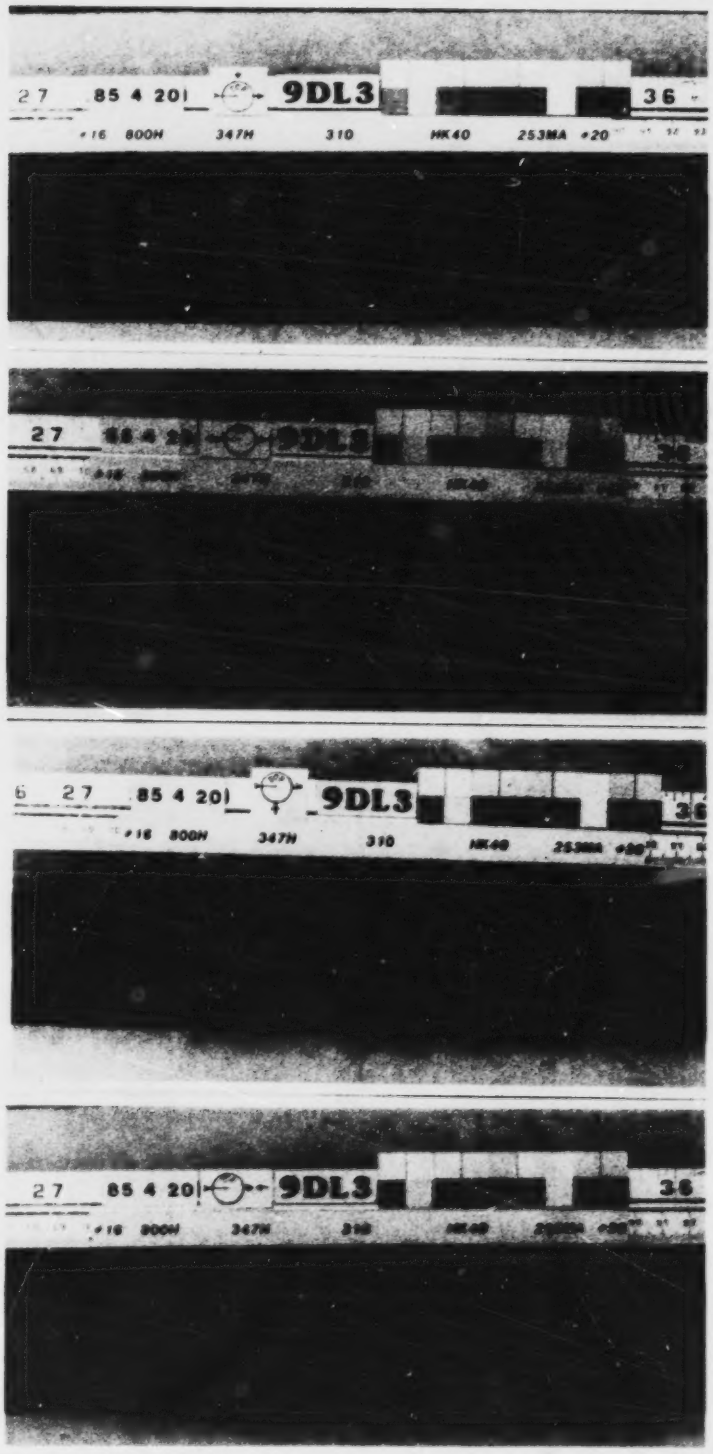


Fig. 23. Coupons 16 to 20 of probe 9DL3.
16/800H, 17/347H, 18/310, 19/HK40, 20/253MA.

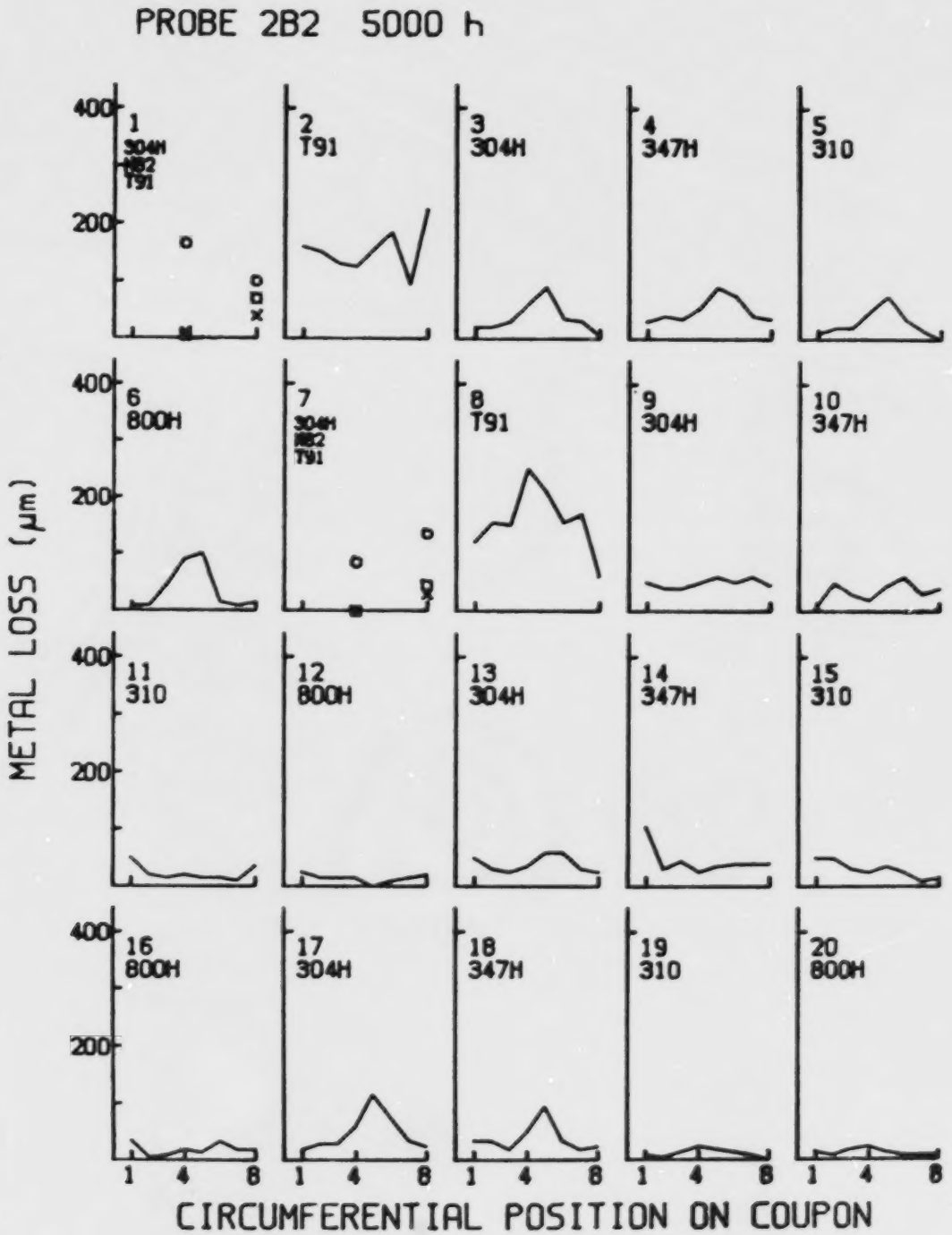


Fig. 24. Plot of metal loss of probe 2B2. For the welded coupons 1 and 7, the symbols are the following: circle - T91, x - N82, square - 304H.

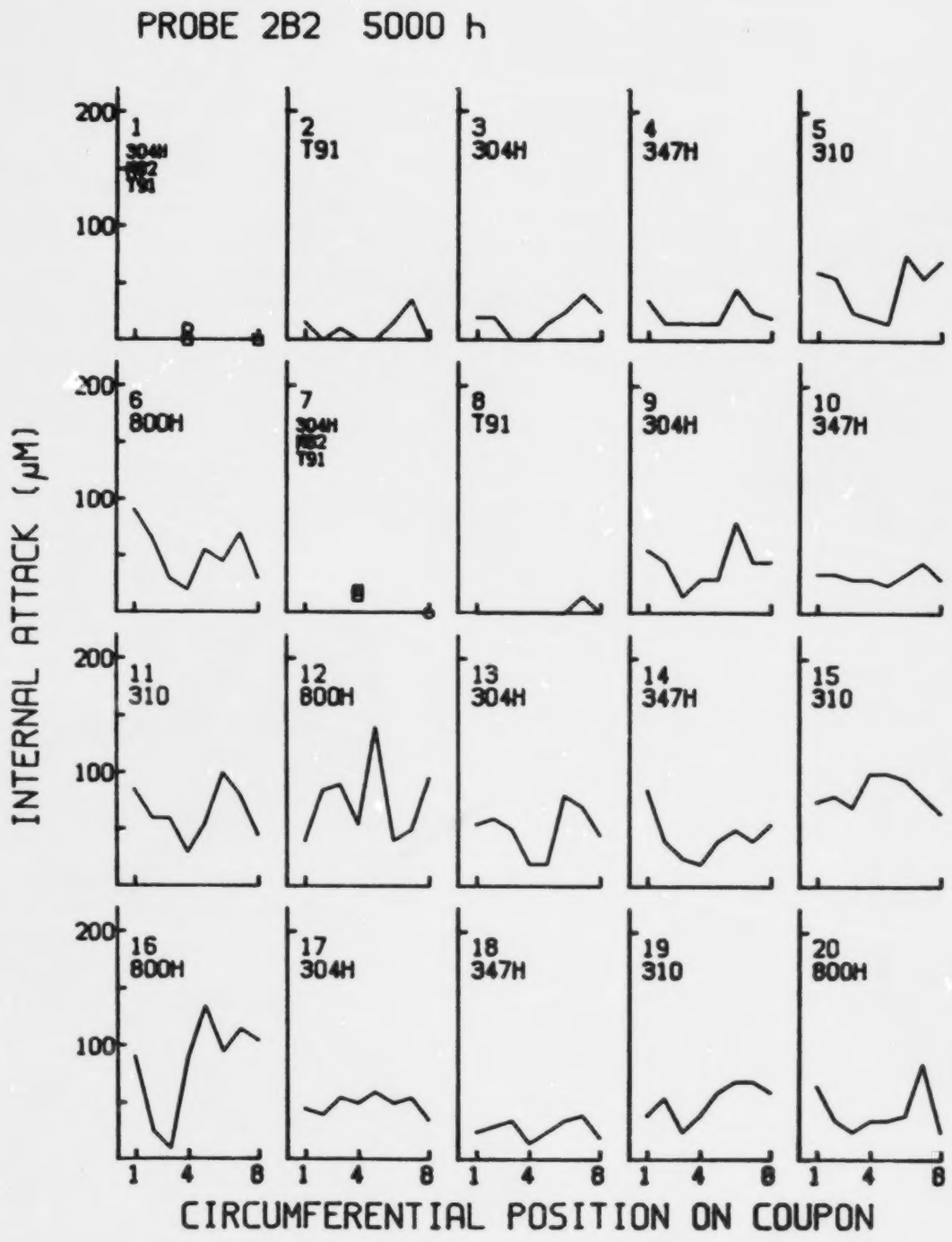


Fig. 25. Plot of internal attack of probe 2B2. See Fig. 24 for welded coupon symbols.

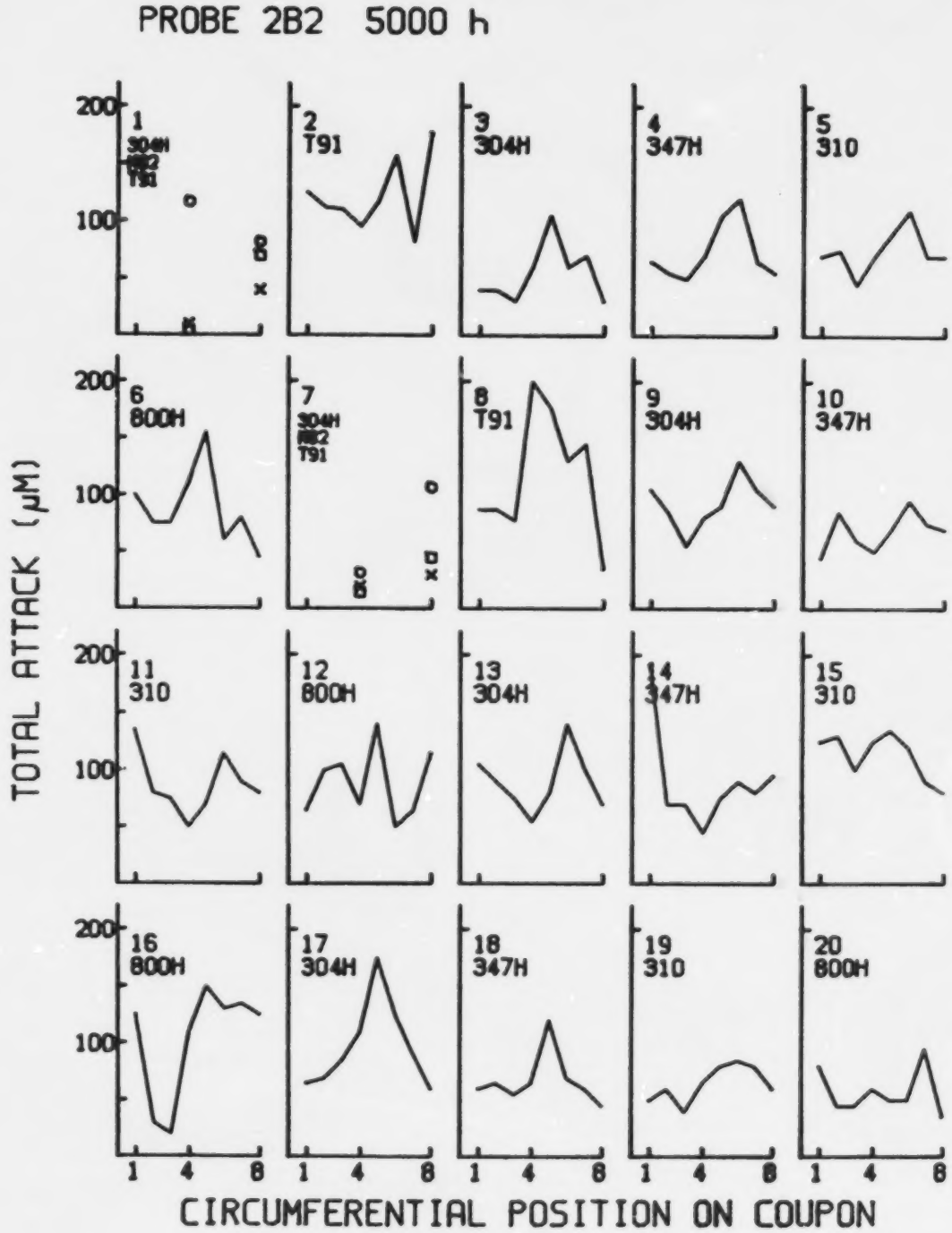


Fig. 26. Plot of total attack of probe 2B2. See Fig. 24 for welded coupon symbols.

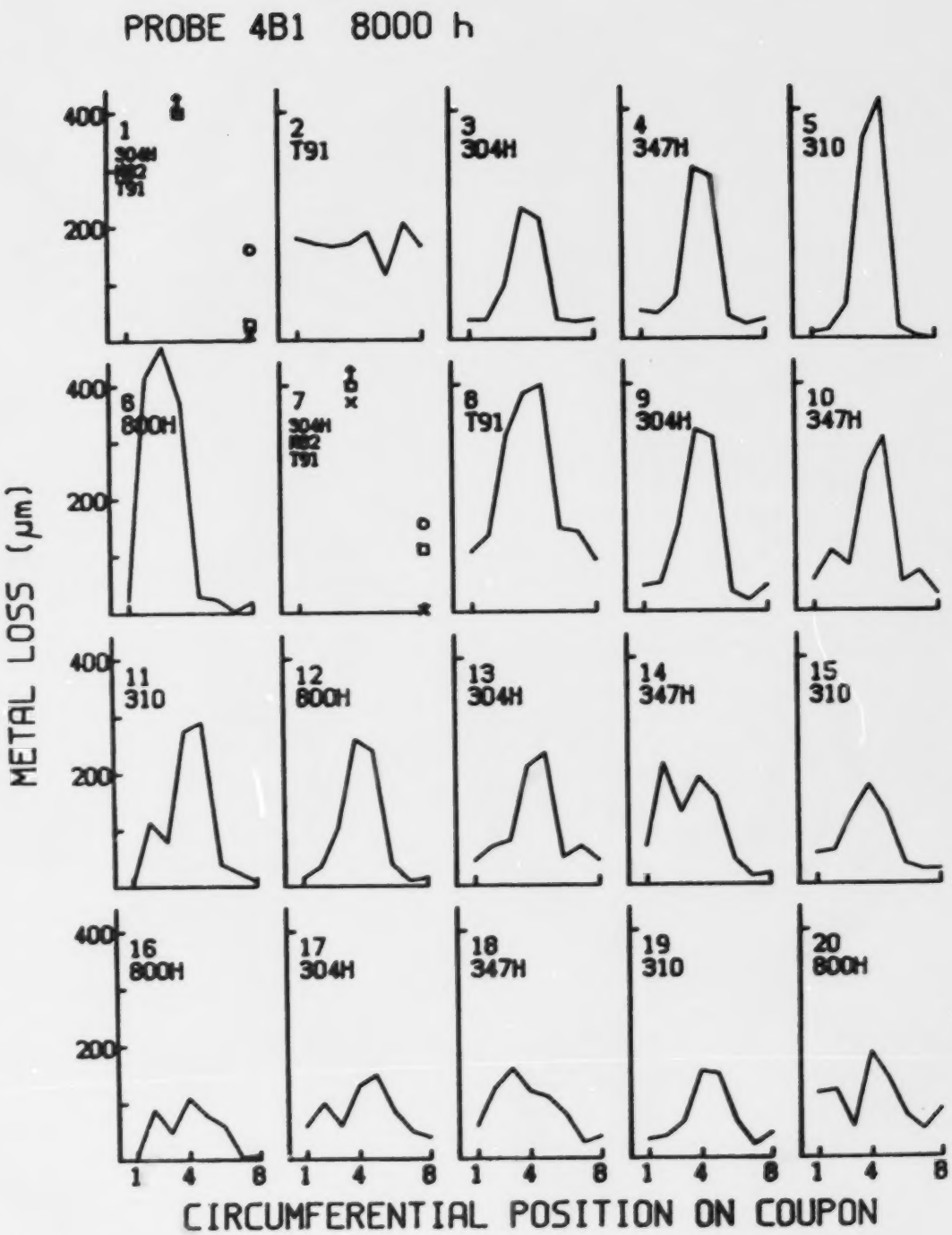


Fig. 27. Plot of metal loss of probe 4B1. See Fig. 24 for welded coupon symbols. Vertical arrow indicates value in excess of 500 μm, see Table 9.

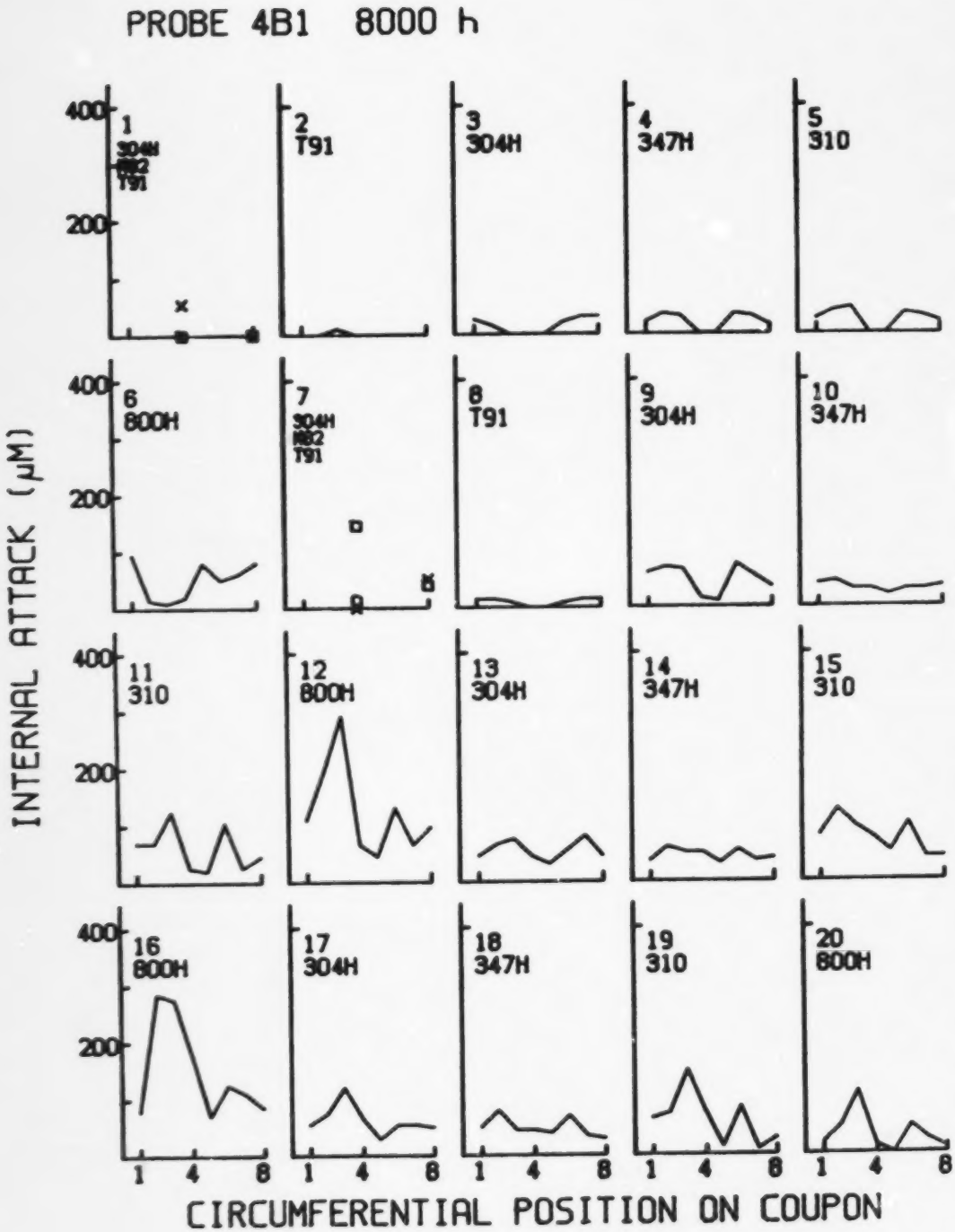


Fig. 28. Plot of internal attack of probe 4B1. See Fig. 24 for welded coupon symbols.

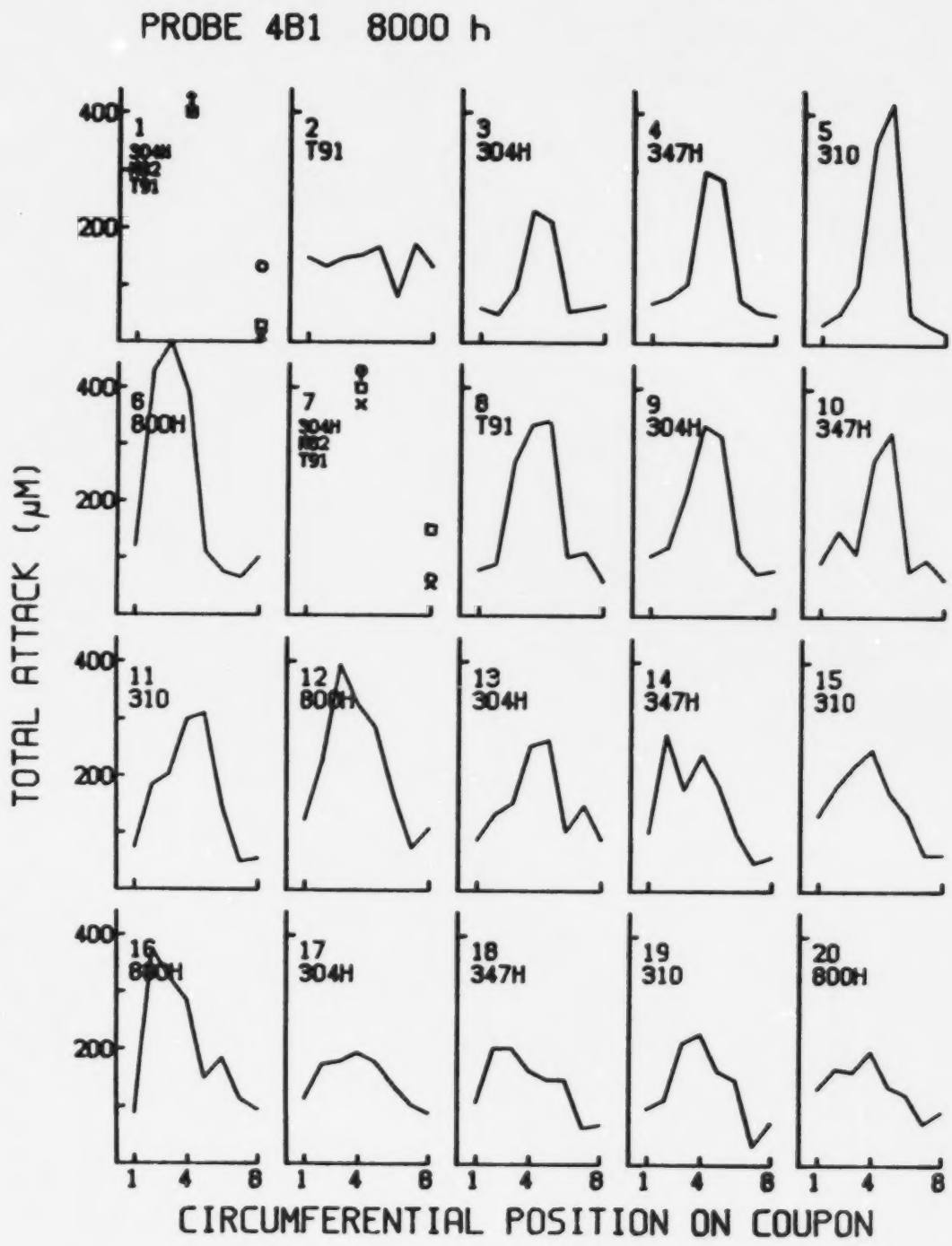


Fig. 29. Plot of total attack of probe 4B1. See Fig. 24 for welded coupon symbols. Vertical arrow indicates value in excess of 500 μm, see Table 11.

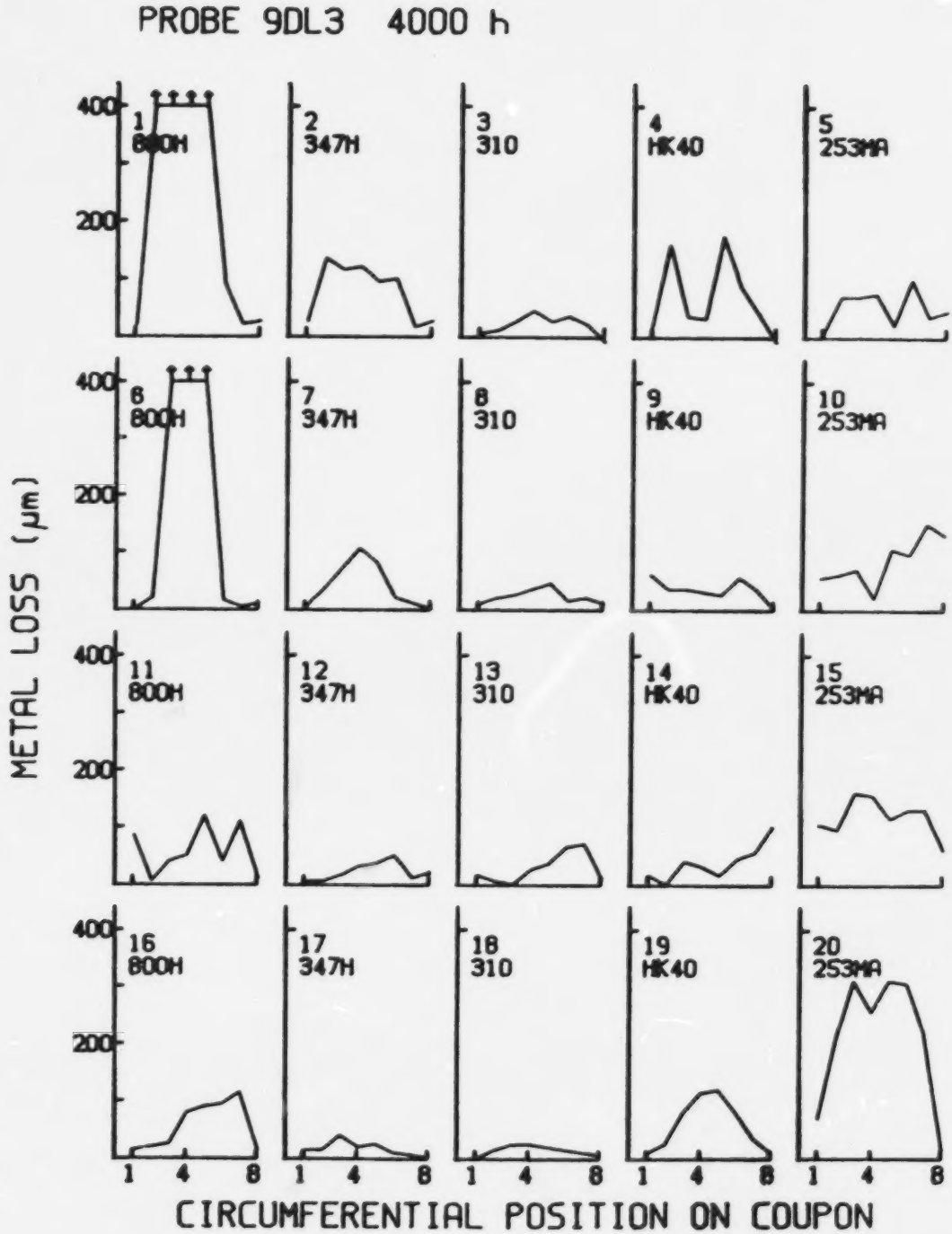


Fig. 30. Plot of metal loss of probe 9DL3. Vertical arrow indicates value in excess of 500 μm, see Table 12.

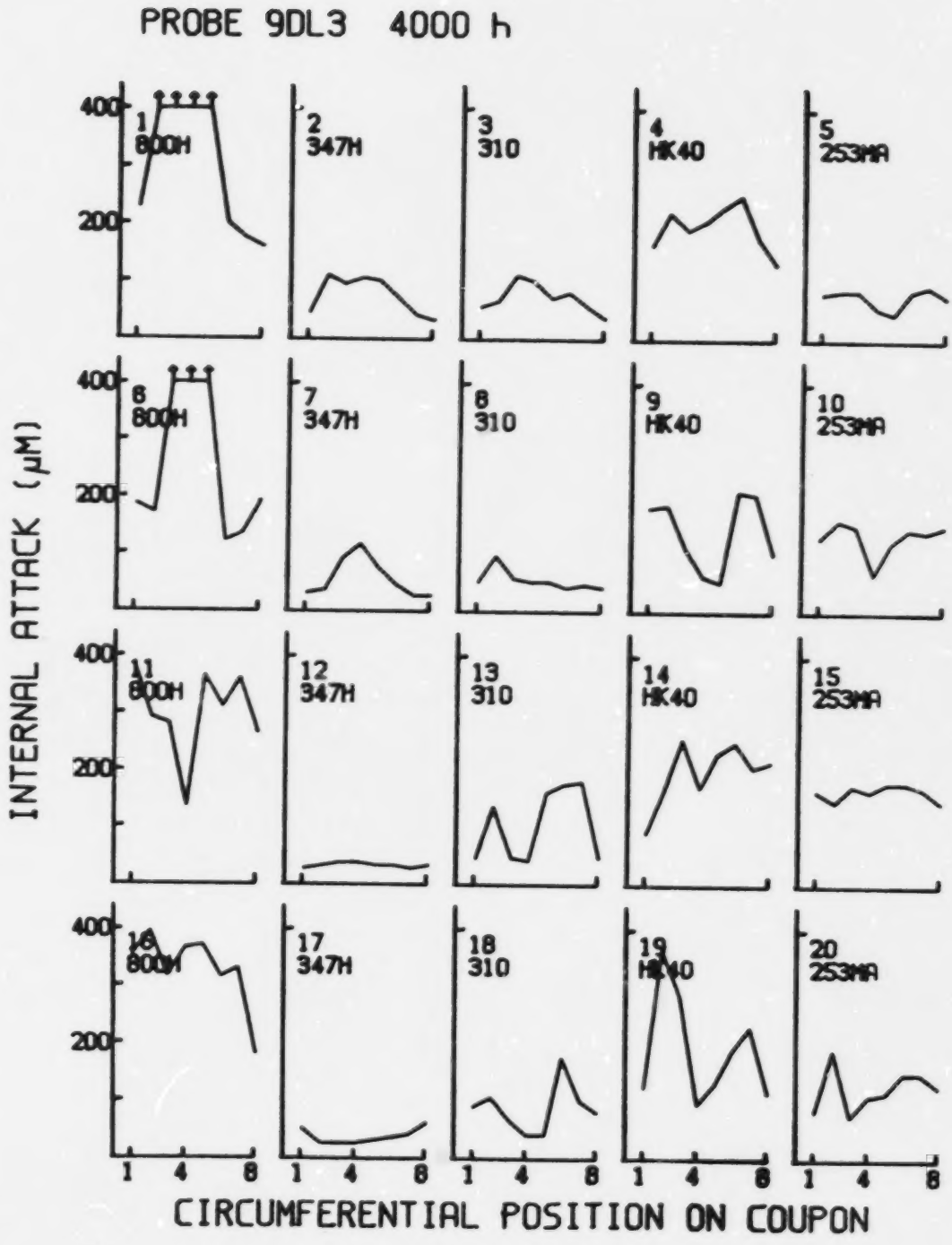


Fig. 31. Plot of internal attack of probe 9DL3. Vertical arrow indicates value in excess of 500 μm, see Table 13.

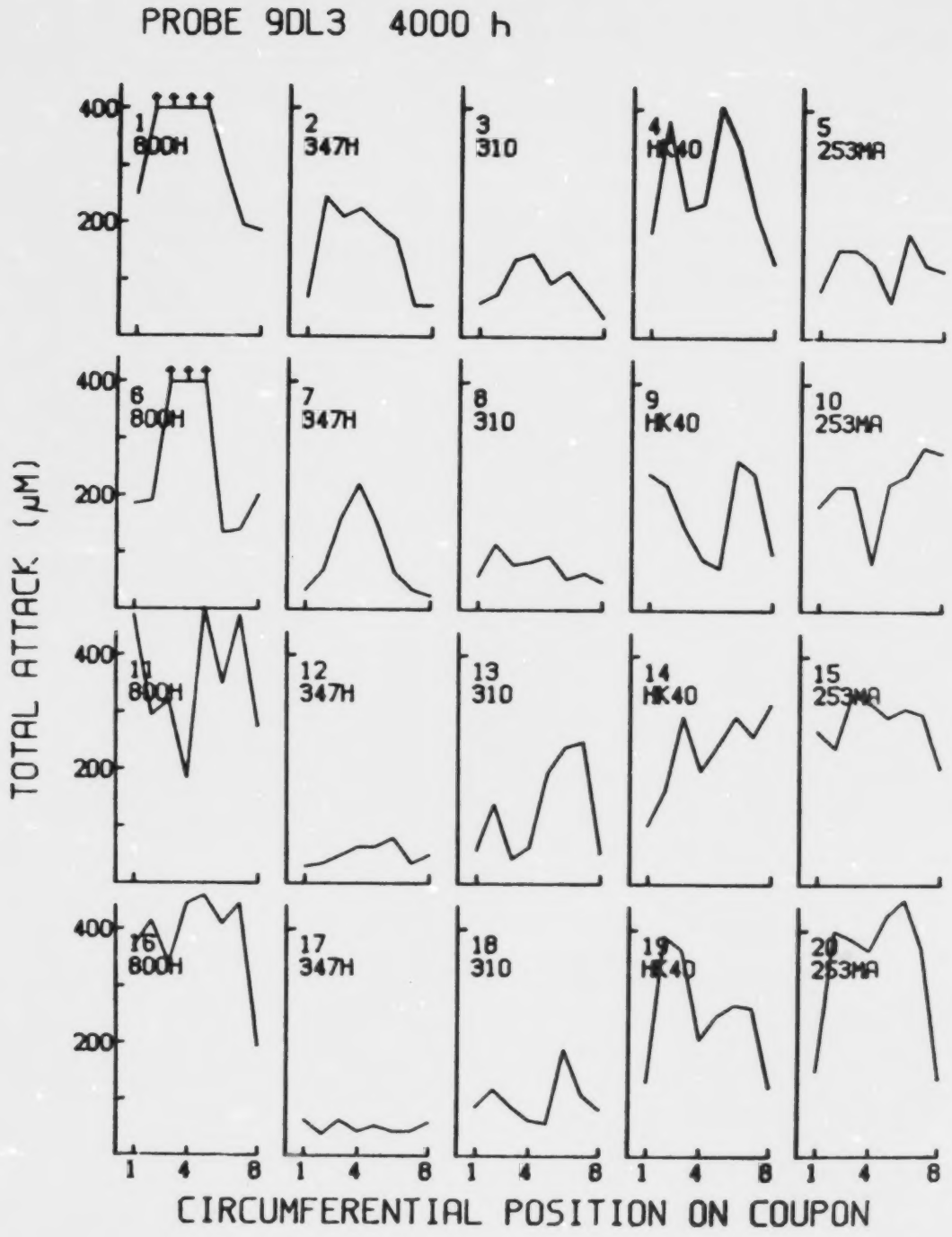


Fig. 32. Plot of total attack of probe 9DL3. Vertical arrow indicates value in excess of 500 μm, see Table 14.

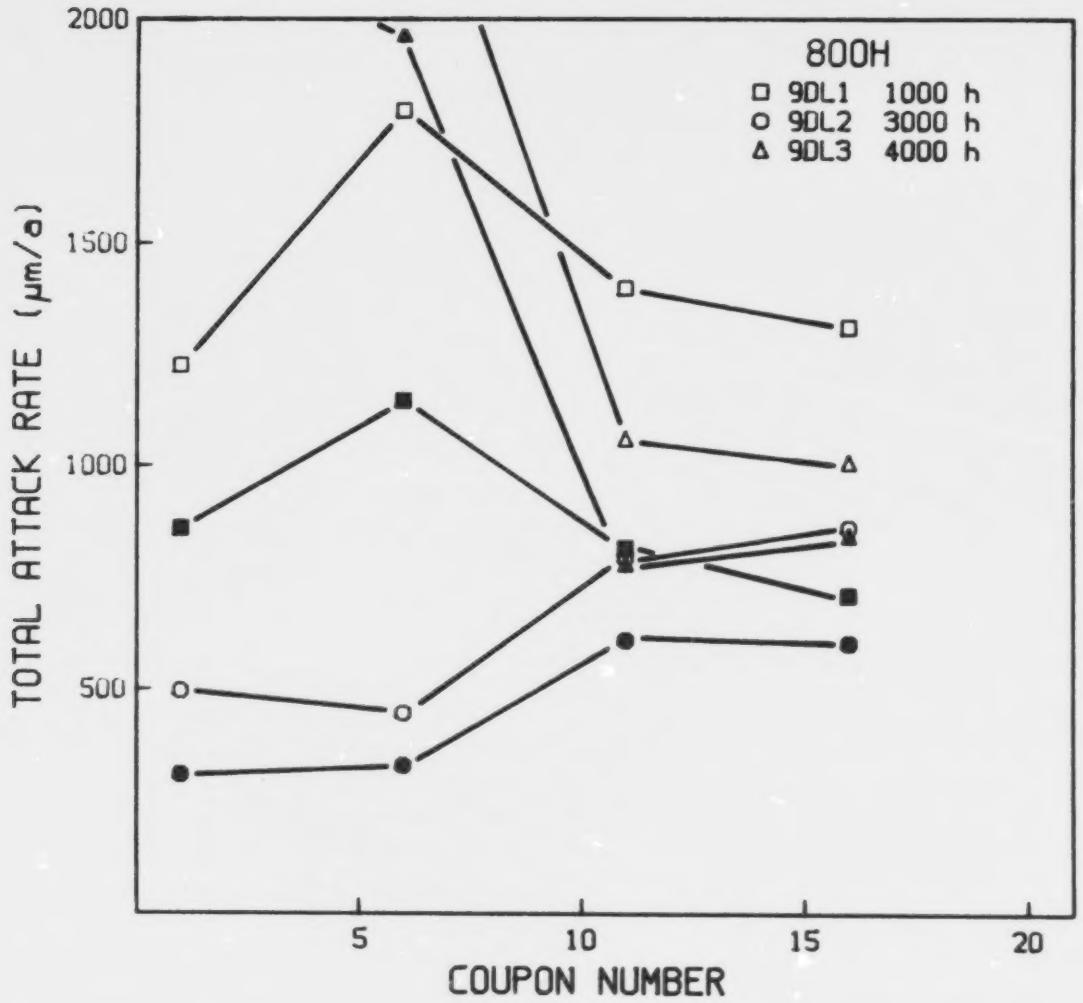


Fig. 33. Maximum (open symbols) and average (closed symbols) total attack rates of 800H in probes 9DL1, 9DL2, and 9DL3.

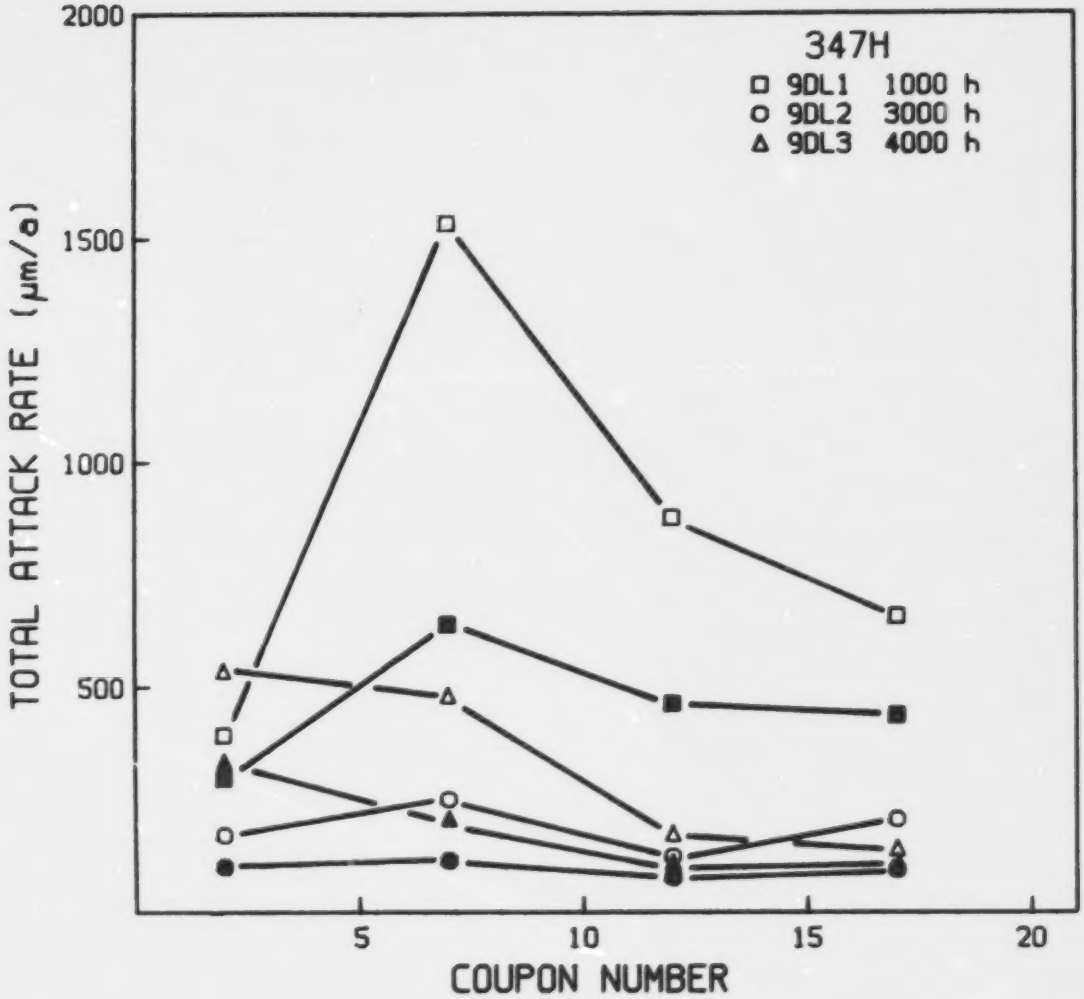


Fig. 34. Maximum (open symbols) and average (closed symbols) total attack rates for the 347H coupons in probes 9DL1, 9DL2 and 9DL3.

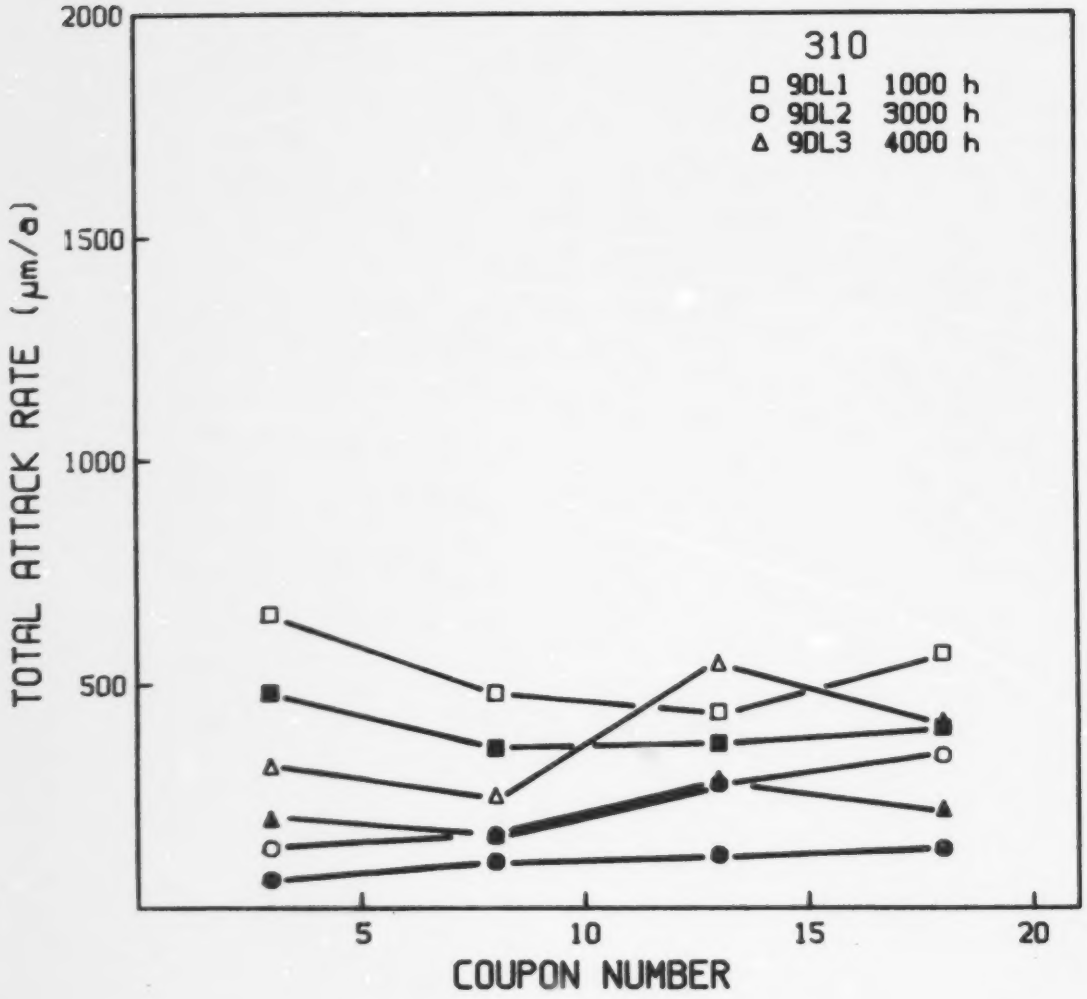


Fig. 35. Maximum (open symbols) and average (closed symbols) total attack rates for the 310 coupons in probes 9DL1, 9DL2 and 9DL3.

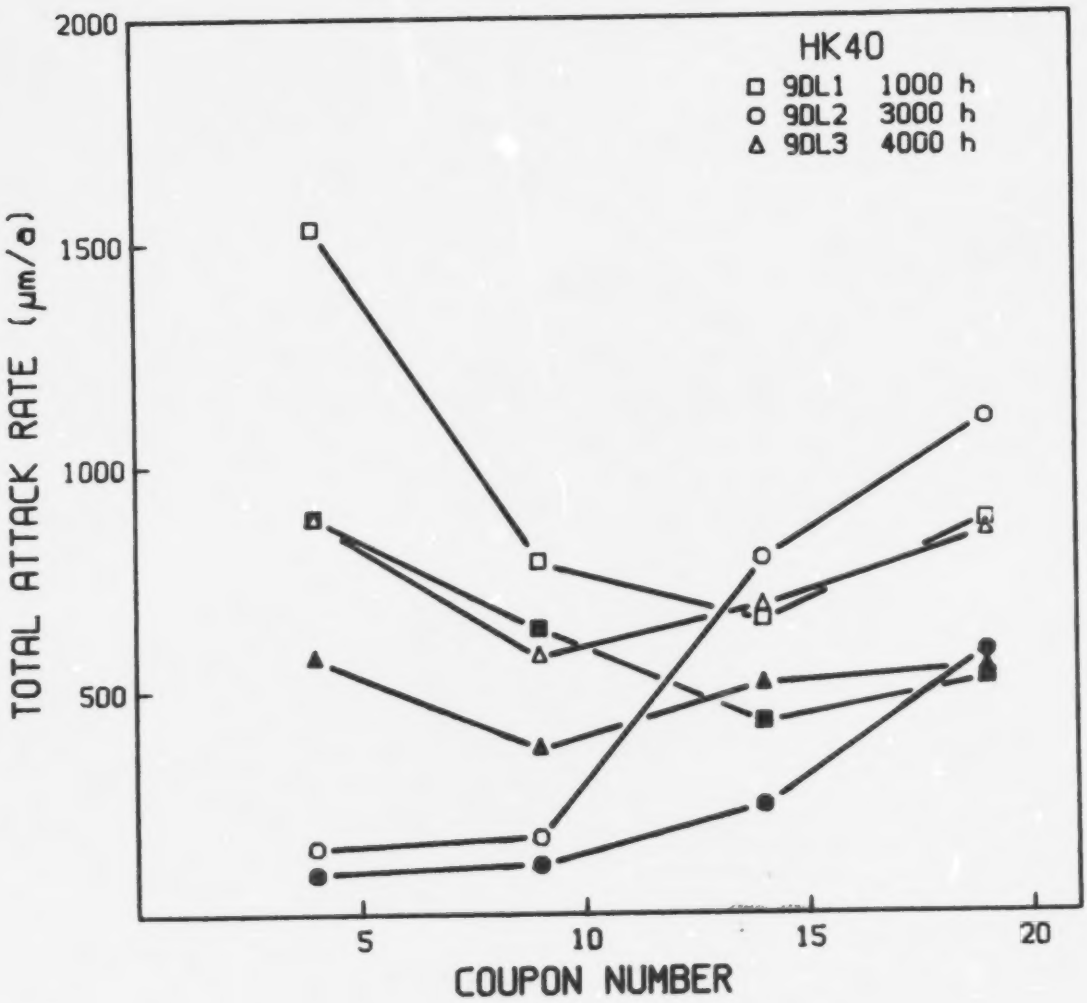


Fig. 36. Maximum (open symbols) and average (closed symbols) total attack rates for the HK40 coupons in probes 9DL1, 9DL2 and 9DL3.

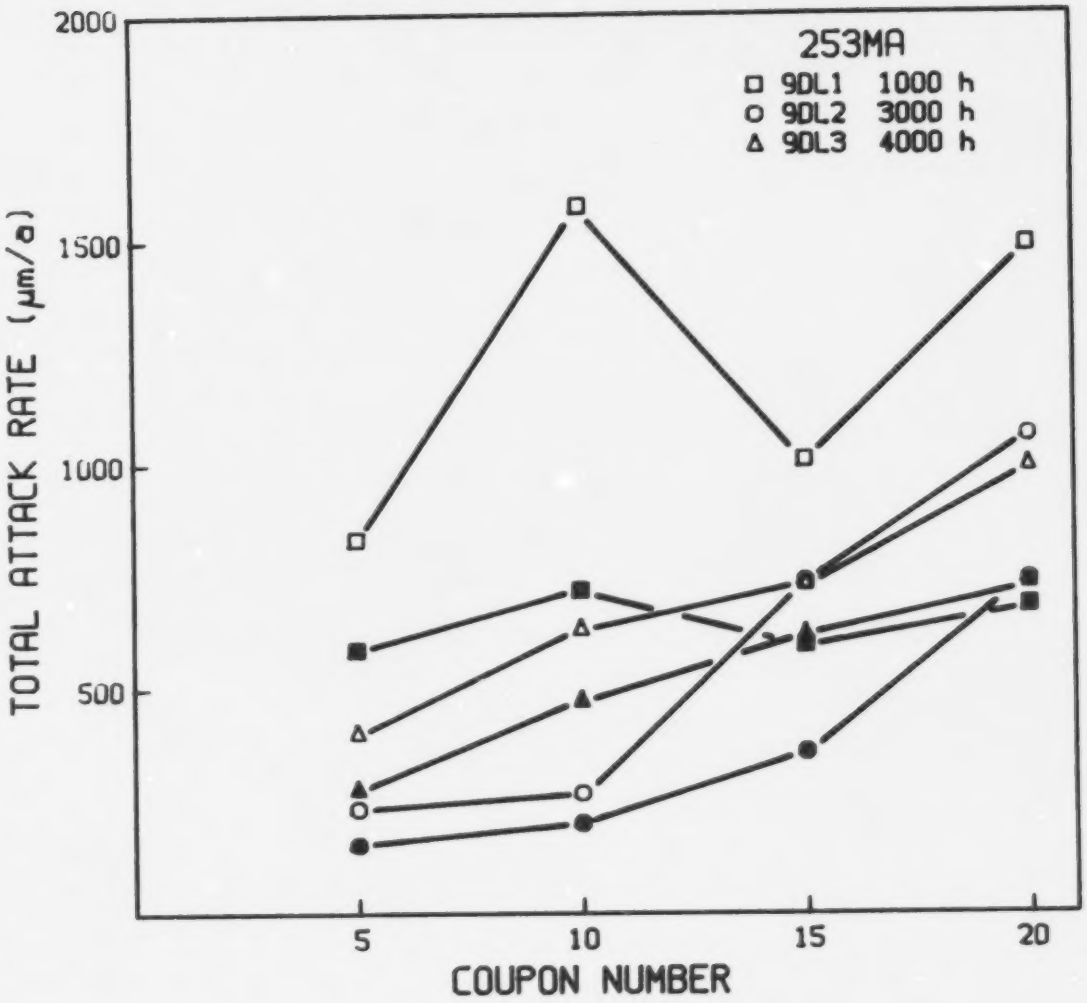


Fig. 37. Maximum (open symbols) and average (closed symbols) total attack rates for the 253MA coupons in probes 9DL1, 9DL2 and 9DL3.

PMRL 86-39 (TR)

APPENDIX 1

DATA SHEETS AND PHOTOMICROGRAPHS

OF

PROBE 2B2

5000-h EXPOSURE

RUNS 5, 6, 7, 8 AND 9

PROBE: 2B2 COUPON: 1 ALLOY: 304H/N82/T91

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 622 C

Bottom : 541 C

Position	4				8		
	304H	N82	T91		304H	N82	T91
Metal Loss	10	5	165		40	70	100
Internal Pen.	TR	--	10		TR	--	TR
Scale	15	10	110		TR	--	70
Deposit	--	--	--		--	--	--
Bore Scale	--	--	115		--	--	35

Hardness - Before Exposure:

After - Top:

Bottom:

Coupon Description:

Top: Somewhat polished, thin, adherent, black scale/deposit. Weld clearly visible; punchmark clearly visible.

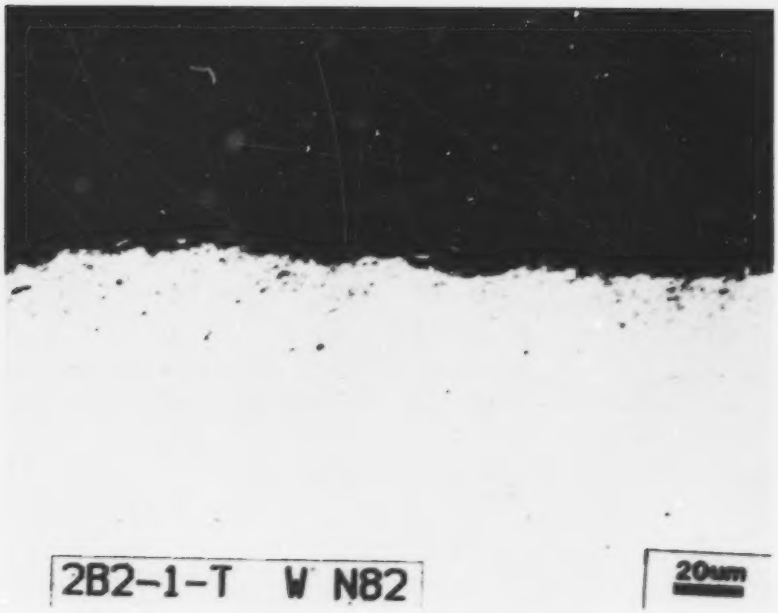
Bottom: Thin, adherent scale/deposit; grey/black on 304H and N82, brown/black on T91.

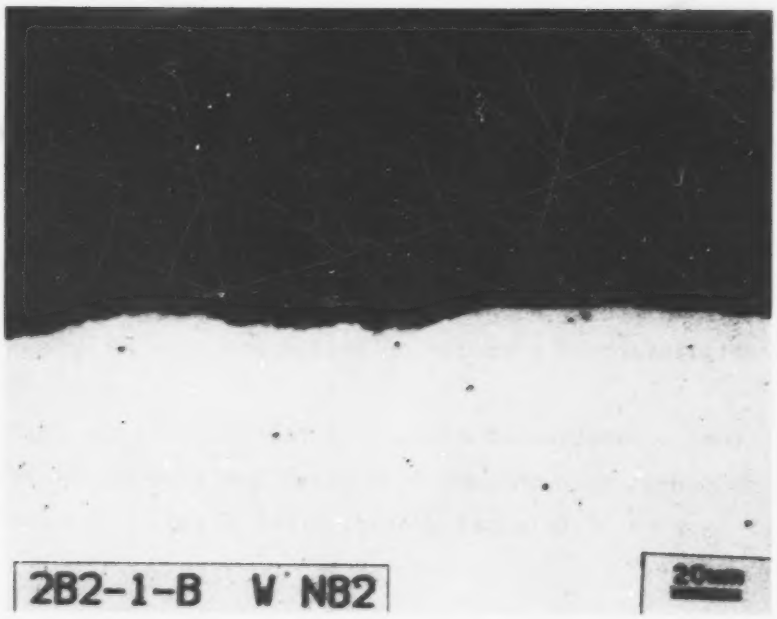
Type of Attack:

Top: N82 - Thin scale, no deposit; irregular scale/metal interface with particles of alloy in scale; very small internal globular precipitates - probably sulphides.

Bottom: N82 - Discontinuous scale, featureless interface.

Other Comments:





Photomicrographs of coupon 1 (N82), probe 2B2.
Top photo - position 8; bottom photo - position 4.

PROBE: 2B2 COUPON: ? ALLOY: T91

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 630 C

Bottom : 553 C

Position	1	2	3	4	5	6	7	8
Metal Loss	160	150	130	125	155	185	95	225
Internal Pen.	15	TR	10	TR	TR	15	35	TR
Scale	90	70	55	60	75	130	65	95
Deposit	80	160	--	--	--	155	45	40
Bore Scale	100	75	60	60	75	85	95	95

Hardness - Before Exposure: 93 RB

After - Top: 89.3 91.0

Bottom: 93.2 93.3

Coupon Description:

Top: Somewhat polished, adherent, black scale/deposit. Punchmark visible, scale/deposit thicker toward coupon 3.

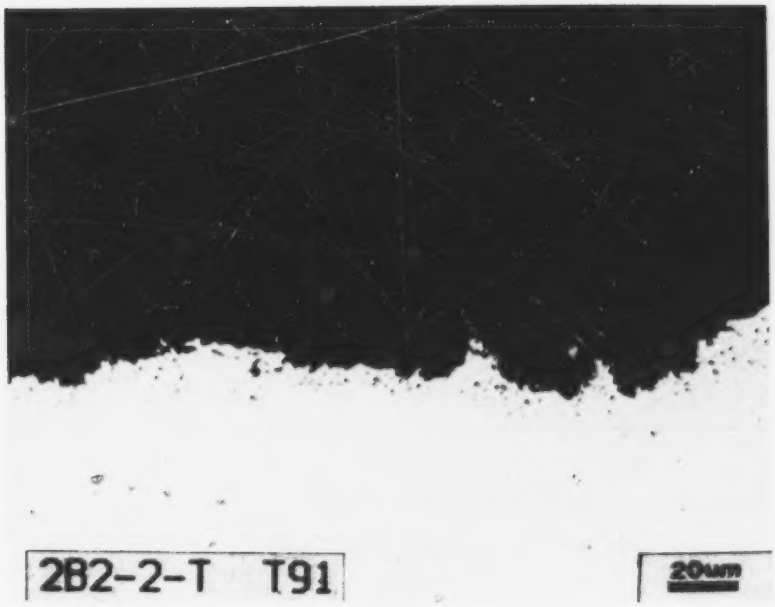
Bottom: Smooth, adherent, black scale/deposit.

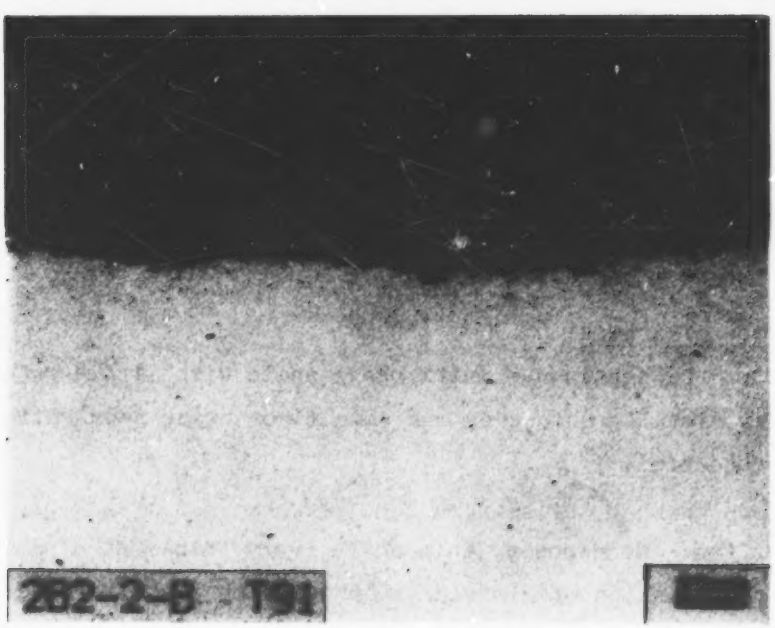
Type of Attack:

Top: Relatively thick multi-phase scale; very non-uniform attack giving an irregular scale/metal interface; a narrow zone of internal precipitation of globular sulphides and perhaps oxides.

Bottom: Character of scale is different from the top and appears more dense; more uniform (but wavy) scale/metal interface, very narrow zone of internal precipitation ahead of the scale/metal interface.

Other Comments:





Photomicrographs of coupon 2 (T91), probe 2B2.

Top photo - position 0.5; bottom photo - position 4.

PROBE: 2B2 COUPON: 3 ALLOY: 304H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 638 C

Bottom : 566 C

Position	1	2	3	4	5	6	7	8
Metal Loss	20	20	30	60	90	35	30	5
Internal Pen.	20	20	TR	TR	15	25	40	25
Scale	20	35	30	10	20	25	15	20
Deposit	10	65	--	--	--	--	TR	--
Bore Scale	10	10	30	15	20	15	10	15

Hardness - Before Exposure: 80 RB

After - Top: 76.3 78.2

Bottom: 80.8 81.1

Coupon Description:

Top: Polished, thin, black scale/deposit. Previously spalled areas, and some spalling to the alloy after removal from the combustor. Punchmark visible.

Bottom: Uniformly thin, matt-grey/black scale/deposit.

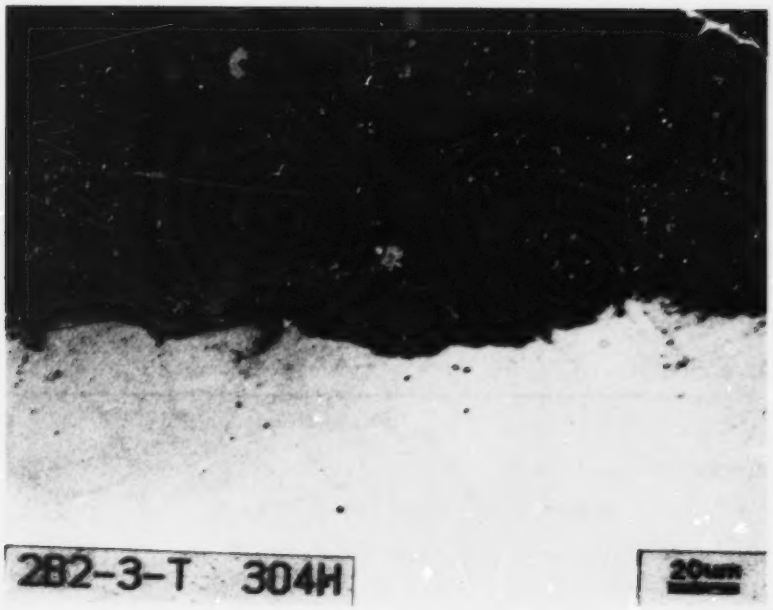
Type of Attack:

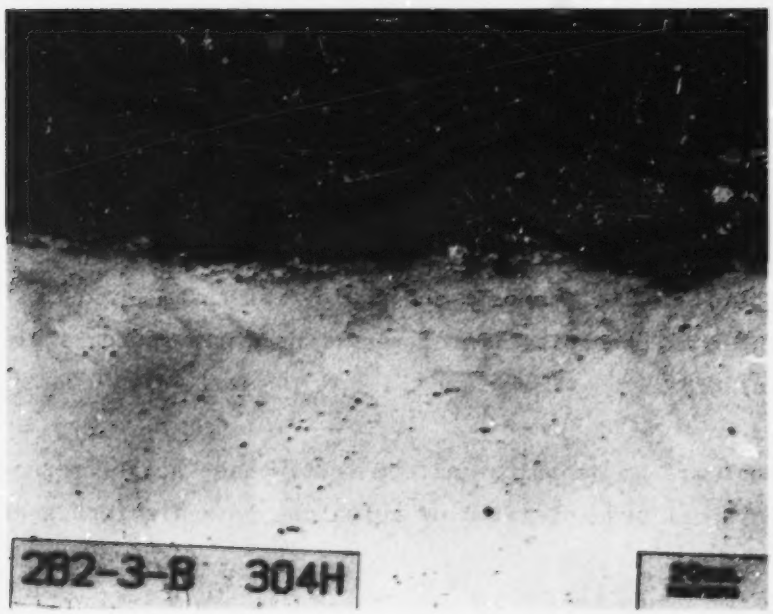
Top: Discontinuous multi-phase scale with little or no deposit; a few globular sulphides and some minor oxide penetration at the grain boundaries.

Bottom: No deposit, thin scale, very thin zone of internal precipitation of globular sulphides immediately ahead of the scale/metal interface in what appears to be a discontinuous metallic zone along the interface separate from the austenitic parent alloy.

Other Comments:

Sample is not etched but there appears to be grain-boundary precipitates throughout the alloy.





Photomicrographs of coupon 3 (304H), probe 2B2.
Top photo - position 8; bottom photo - position 4.

PROBE: 2B2 COUPON: 4 ALLOY: 347H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 646 C

Bottom : 579 C

Position	1	2	3	4	5	6	7	8
Metal Loss	30	40	35	55	90	75	40	35
Internal Pen.	35	15	15	15	15	45	25	20
Scale	15	10	20	10	15	15	20	20
Deposit	40	25	20	--	15	30	55	35
Bore Scale	20	15	15	25	35	20	25	25

Hardness - Before Exposure: 81 RB

After - Top: 83.2 84.0

Bottom: 84.9 85.2

Coupon Description:

Top: Polished, black scale/deposit of varying thickness resulting from spalling. Some new spalling to a tan/pink deposit and to the alloy.

Bottom: Uniformly thin, matt-grey/black scale/deposit.

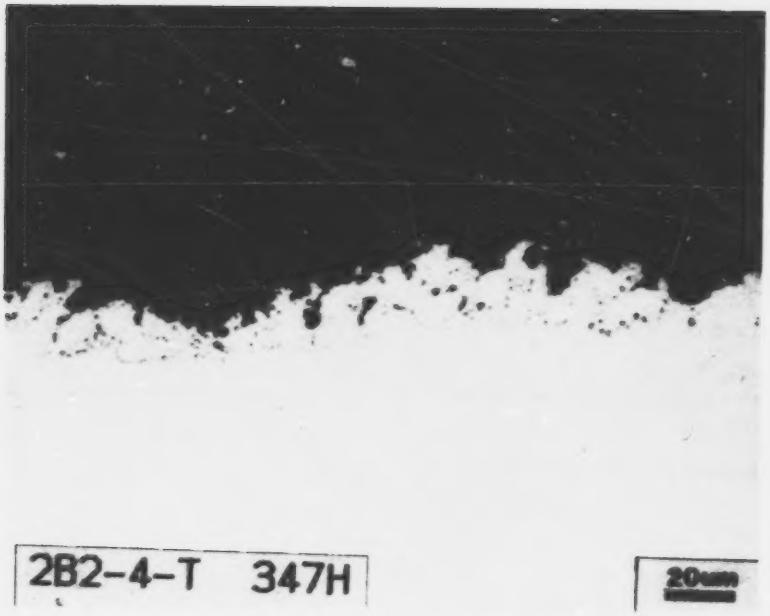
Type of Attack:

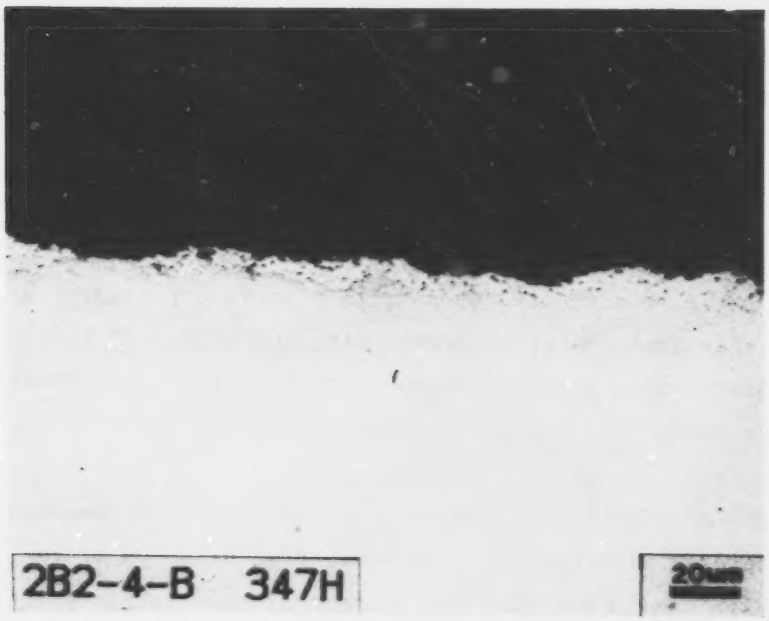
Top: Distinct deposit and scale, irregular scale/metal interface; internal precipitation of very fine grain-boundary globular sulphides.

Bottom: No deposit, uniform multi-phase scale; zone of very fine internal precipitation of sulphides in a distinct surface zone.

Other Comments:

There appears to be grain-boundary precipitates throughout much of the alloy.





Photomicrographs of coupon 4 (347H), probe 2B2.
Top photo - position 8; bottom photo - position 4.

PROBE: 2B2 COUPON: 5 ALLOY: 310

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 654 C

Bottom : 591 C

Position	1	2	3	4	5	6	7	8
Metal Loss	10	20	20	50	75	35	15	--
Internal Pen.	60	55	25	20	15	75	55	70
Scale	20	30	25	25	35	20	25	30
Deposit	240	165	35	--	--	275	210	90
Bore Scale	10	--	15	--	TR	--	TR	--

Hardness - Before Exposure: 82 RB

After - Top: 87.8 87.0

Bottom: 85.1 85.7

Coupon Description:

Top: Polished, multi-layered, black scale/deposit. Obviously spalled previously, and after removal from the combustor to tan/pink, brown and black layers.

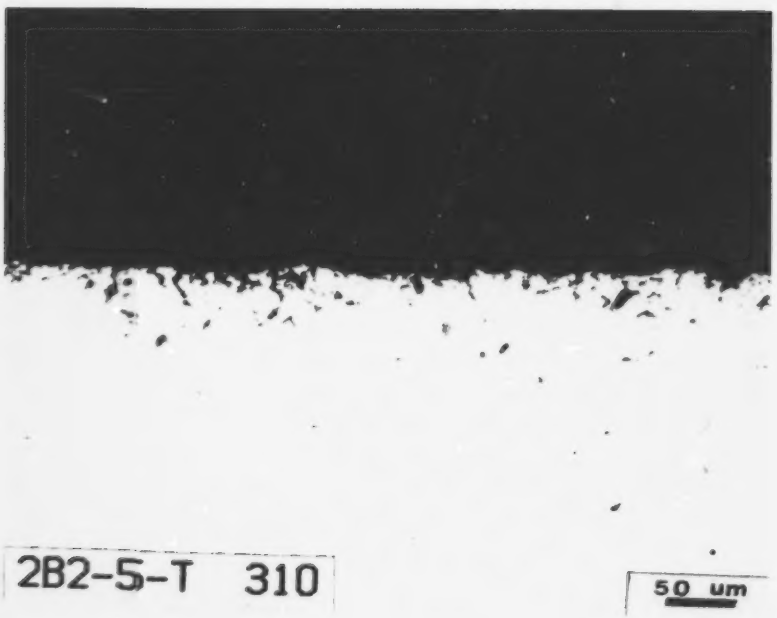
Bottom: Uniformly thin, matt-grey/black scale/deposit.

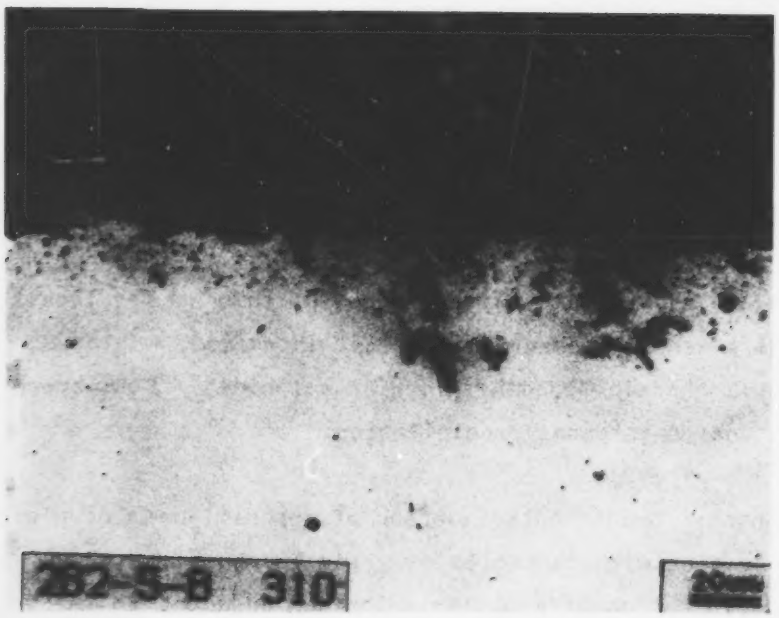
Type of Attack:

Top: Discontinuous deposit, thin scale (spalled in many areas); planar scale/metal interface with intrusions of scale into the alloy. Some grain-boundary sulphides, but to no greater depth than the scale intrusions. Internal attack is not uniformly distributed.

Bottom: Similar to top, but no deposit and a somewhat wavy scale/metal interface. Internal precipitation of very fine globular sulphides in what appears to be a distinct surface zone not present at the top of the coupon.

Other Comments:





Photomicrographs of coupon 5 (310), probe 2B2.
Top photo - position 7.3; bottom photo - position 2.7.

PROBE: 2B2 COUPON: 6 ALLOY: 800H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 661 C

Bottom : 604 C

Position	1	2	3	4	5	6	7	8
Metal Loss	10	10	45	90	100	15	10	15
Internal Pen.	90	65	30	20	55	45	70	30
Scale	15	30	20	20	45	25	25	15
Deposit	485	200	30	20	20	100	185	190
Bore Scale	TR	--	--	--	--	TR	TR	TR

Hardness - Before Exposure: 69 RB

After - Top: 81.2 80.7

Bottom: 82.0 81.0

Coupon Description:

Top: Polished, multi-layered, black scale/deposit. Spalled previously, and after removal from the combustor to brown, tan/pink or black layers and to the alloy surface.

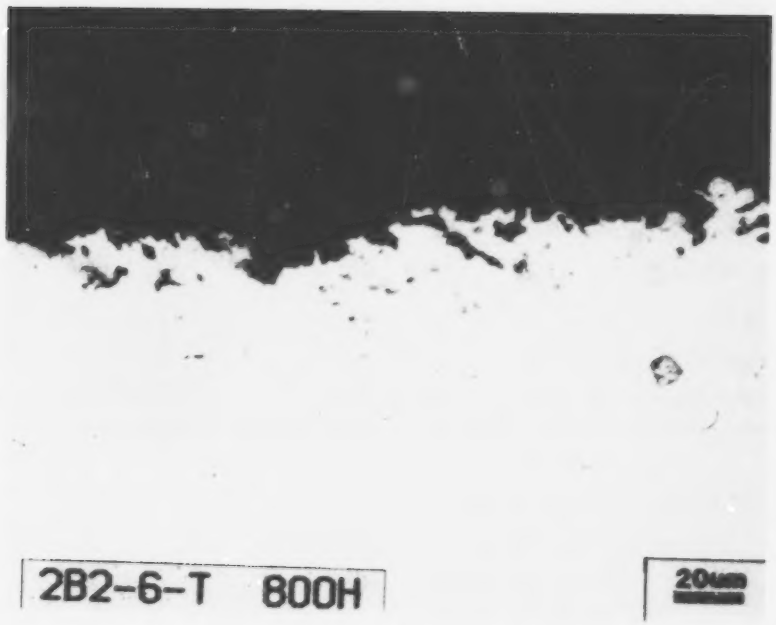
Bottom: Uniformly thin, matt- grey/black scale/deposit.

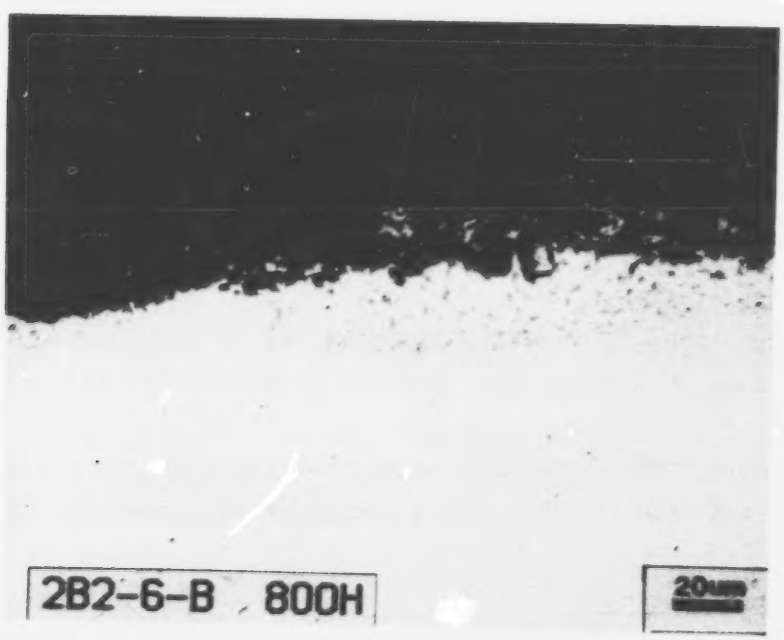
Type of Attack:

Top: Thick, multi-layered deposit, thin scale; locally irregular but generally planar scale/metal interface. Internal precipitation of fine grain-boundary globular sulphides. Some areas of more extensive internal precipitation.

Bottom: Smooth outer surface of deposit; breakdown of scale/metal interface with particles of alloy in the scale. Zone of internal precipitation of globular sulphides adjacent to the interface.

Other Comments:





Photomicrographs of coupon 6 (800H), probe 2B2.
Top photo - position 0.2; bottom photo - position 4.

PROBE: 2B2 COUPON: 7 ALLOY: 304H/N82/T91

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 669 C

Bottom : 616 C

Position	4				8		
	304H	N82	T91		304H	N82	T91
Metal Loss	--	--	85		30	45	135
Internal Pen.	20	15	20		TR	TR	--
Scale	25	15	110		35	55	195
Deposit	--	--	--		--	--	--
Bore Scale	15	15	145		10	TR	55

Hardness - Before Exposure:

After - Top:

Bottom:

Coupon Description:

Top: Polished, thin, black scale/deposit on 304H and N82. Polished thick, rough surfaced deposit on T91.

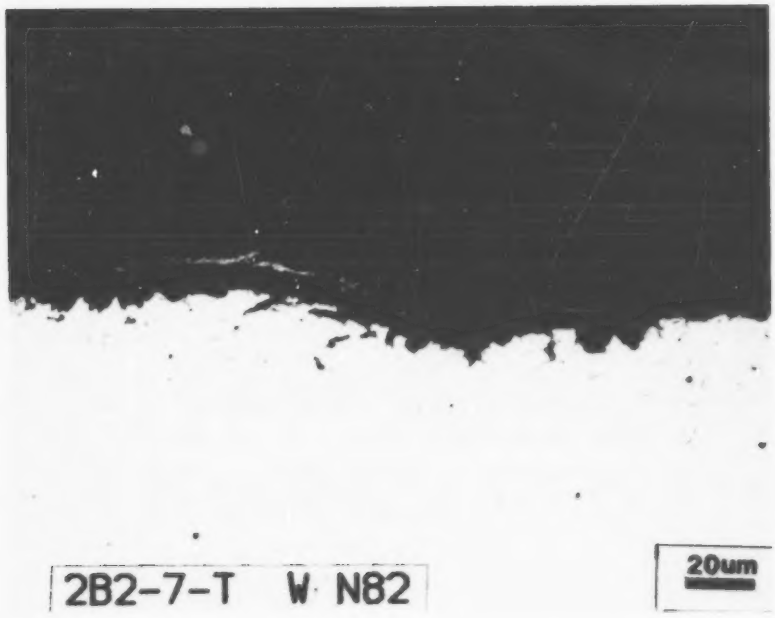
Bottom: Weld visible; uniformly thin, matt-black scale/deposit on 304H and N82. Thicker matt-black scale/deposit on T91.

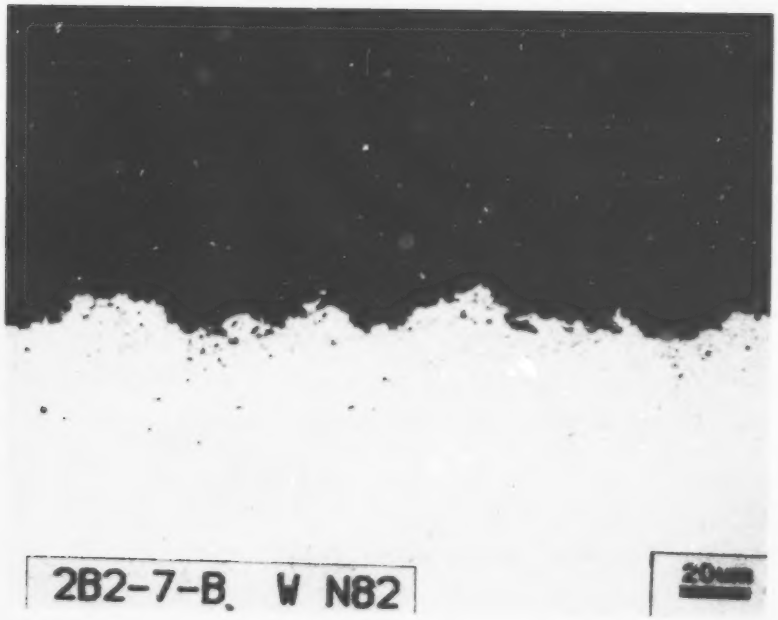
Type of Attack:

Top: N82 - Thin scale, locally irregular scale/metal interface with a zone of internal precipitation of globular sulphides.

Bottom: N82 - Somewhat more irregular scale/metal interface than at top with internal precipitation of very fine globular sulphides.

Other Comments:





Photomicrographs of coupon 7 (N82), probe 2B2.
Top photo - position 8; bottom photo - position 4.

PROBE: 2B2 COUPON: 8 ALLOY: T91

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 677 C

Bottom : 629 C

Position	1	2	3	4	5	6	7	8
Metal Loss	120	155	150	250	210	155	170	60
Internal Pen.	--	--	--	TR	--	--	15	--
Scale	100	95	110	220	165	110	140	60
Deposit	400	1500	470	125	55	1720	970	160
Bore Scale	65	135	145	100	65	50	80	50

Hardness - Before Exposure: 93 RB

After - Top: 84.9 86.8

Bottom: 94.8 95.0

Coupon Description:

Top: Polished, thick, rough surfaced, black scale/deposit; very thick on sides of coupon.

Bottom: Uniform, matt-grey/black scale/deposit.

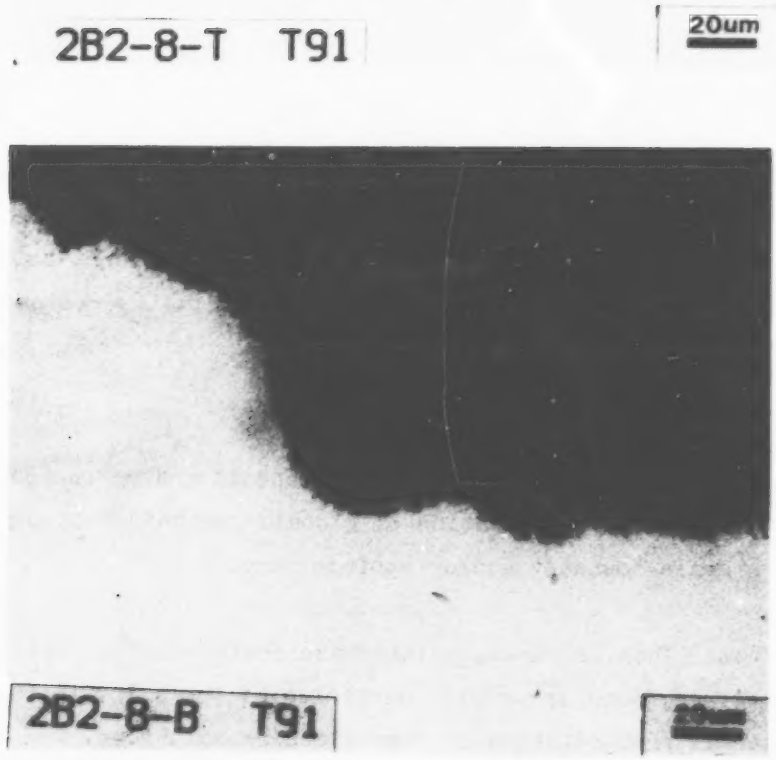
Type of Attack:

Top: Very thick multi-layered deposit. Very non-uniform attack of metal giving an almost "pitted" appearing section.

Bottom: Thinner deposit than at top, intermitent zone of internal precipitation immediately adjacent to the scale/metal interface. A few very fine globular sulphides in some areas.

Other Comments:

Deposit thickest on the sides (positions 2 and 6) of the coupon.



Photomicrographs of coupon 8 (T91), probe 2B2.
Top photo - position 7.9; bottom photo - position 1.2.

PROBE: 2B2 COUPON: 9 ALLOY: 304H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 682 C

Bottom : 638 C

Position	1	2	3	4	5	6	7	8
Metal Loss	50	40	40	50	60	50	60	45
Internal Pen.	55	45	15	30	30	80	45	45
Scale	20	20	15	40	55	35	35	15
Deposit	120	80	50	110	--	30	160	50
Bore Scale	25	15	10	15	15	15	25	20

Hardness - Before Exposure: 80 RB

After - Top: 75.2 77.4

Bottom: 78.5 79.7

Coupon Description:

Top: Polished, relatively thin, black scale/deposit. Spalled to tan/brown intermediate layers and to the alloy surface.

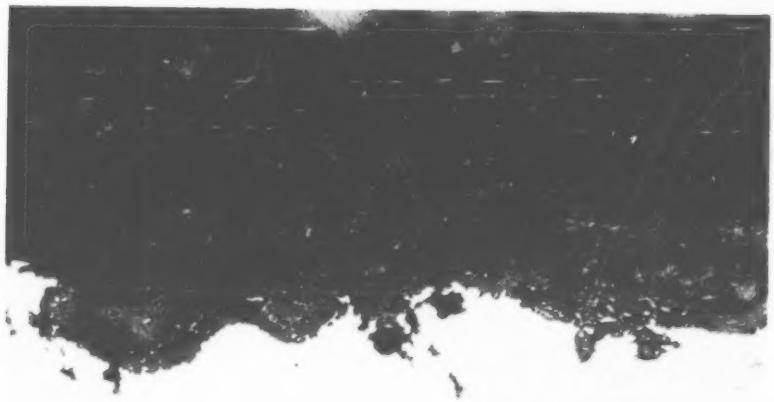
Bottom: Thin, matt-black scale/deposit with micro-spalling to a grey scale on bottom centre. Thicker, multi-layered deposits on sides.

Type of Attack:

Top: Thin scale, irregular scale/deposit and scale/metal interface; some internal precipitation of globular sulphides that appear to be in a grain-boundary and/or surface zone.

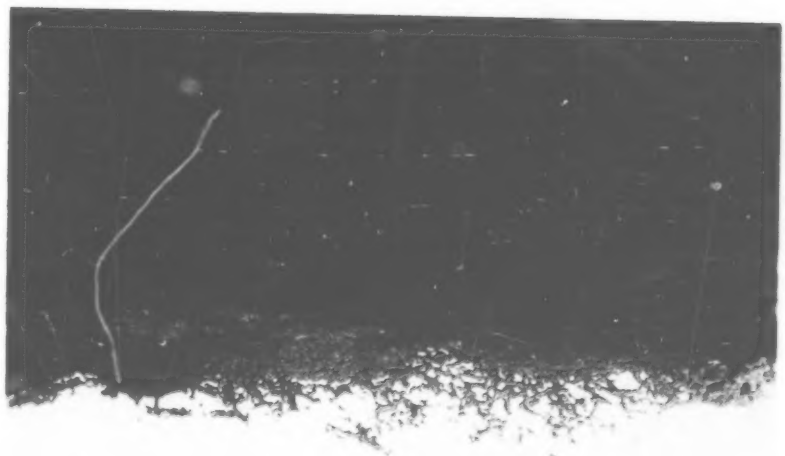
Bottom: Thin, layered, multi-phase scale; diffuse scale/metal interface, some areas with particles of the alloy in the scale. Internal precipitation of fine globular sulphides.

Other Comments:



2B2-9-T 304H

20um



2B2-9-B 304H

20um

Photomicrographs of coupon 9 (304H), probe 2B2.
Top photo - position 7.8; bottom photo - position 3.9.

PROBE: 2B2 COUPON: 10 ALLOY: 347H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 686 C

Bottom : 646 C

Position	1	2	3	4	5	6	7	8
Metal Loss	10	50	30	20	45	60	30	40
Internal Pen.	35	35	30	30	25	35	45	30
Scale	15	15	20	20	30	35	50	20
Deposit	25	130	100	100	50	180	190	40
Bore Scale	15	10	10	10	10	15	15	25

Hardness - Before Exposure: 81 RB

After - Top: 82.2 82.1

Bottom: 81.0 82.0

Coupon Description:

Top: Polished, thin, black, scale/deposit; spalled to alloy over large areas on the sides.

Bottom: Thin, black scale/deposit with micro-spalling on centre; thicker multi-layered deposit towards sides.

Type of Attack:

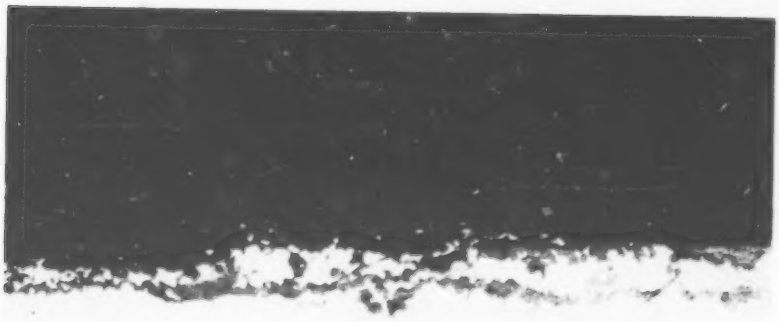
Top: Layered appearing scale/deposit; locally irregular scale/metal interface. Some scale intrusions into alloy. Precipitation of globular sulphides associated with a grain-boundary or surface zone.

Bottom: Irregular scale/metal interface with intrusions of scale into the alloy. Precipitation of globular sulphides in a surface zone. Several areas of the specimen are similar to the micrograph in that there is a scale "front" formed internally in the alloy.

Other Comments:

Precipitation of a grain-boundary precipitates throughout alloy. Analyze scale "front" with EPMA.

2B2-10-T 347H 20um



2B2-10-B 347H 20um

Photomicrographs of coupon 10 (347H), probe 2B2.
Top photo - position 7.8; bottom photo - position 4.

PROBE: 2B2 COUPON: 11 ALLOY: 310

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 691 C

Bottom : 655 C

Position	1	2	3	4	5	6	7	8
Metal Loss	50	20	15	20	15	15	10	35
Internal Pen.	85	60	60	30	55	100	80	45
Scale	15	15	10	15	25	15	10	20
Deposit	30	350	150	980	550	385	160	10
Bore Scale	15	15	15	20	20	15	TR	15

Hardness - Before Exposure: 82 RB

After - Top: 87.3 85.3

Bottom: 86.5 85.5

Coupon Description:

Top: Polished, relatively thin, black scale/deposit; small areas spalled to the alloy; some prior spalling.

Bottom: Relatively thick, eroded appearing, matt-black scale/deposit that seems to be composed of several layers.

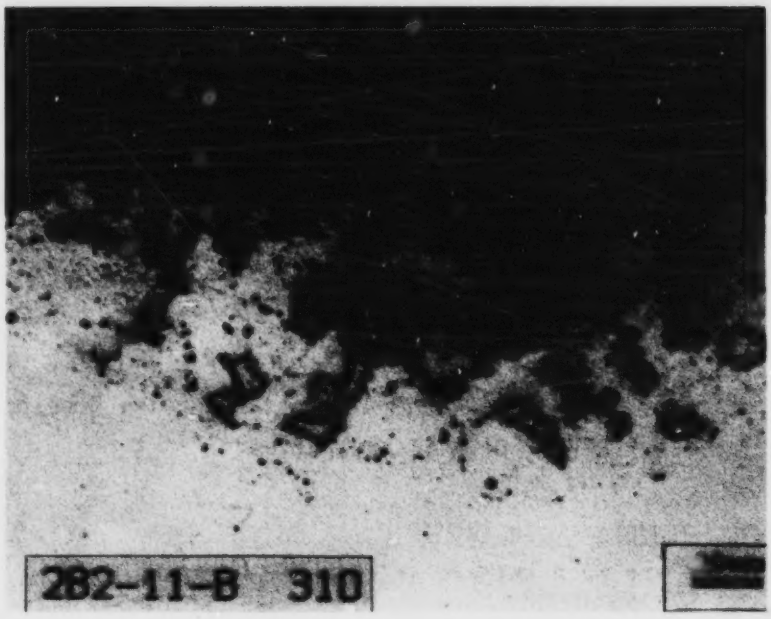
Type of Attack:

Top: Little deposit, thin scale, relatively uniform scale/metal interface on a macro scale. Precipitation of globular sulphides, primarily at the grain boundaries.

Bottom: Very thick deposit (1 mm) in some areas, diffuse scale/metal interface in local areas, internal precipitation of oxides and sulphides.

Other Comments:

Deposit is thickest on the bottom of the coupon, and very thin on the top.



Photomicrographs of coupon 11 (310), probe 2B2.
Top photo - position 7.5; bottom photo - position 5.4.

PROBE: 2B2 COUPON: 12 ALLOY: 800H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 695 C

Bottom : 663 C

Position	1	2	3	4	5	6	7	8
Metal Loss	25	15	15	15	--	10	15	20
Internal Pen.	40	85	90	55	140	40	50	95
Scale	30	20	15	25	50	25	15	20
Deposit	30	545	90	620	1800	495	80	20
Bore Scale	TR	TR	TR	--	TR	--	--	TR

Hardness - Before Exposure: 69 RB

After - Top: 78.5 78.2

Bottom: 80.8 80.0

Coupon Description:

Top: Polished, uniform, black scale/deposit, punchmark just visible.

Bottom: Relatively thick, eroded-appearing, black, multi-layered, scale/deposit.

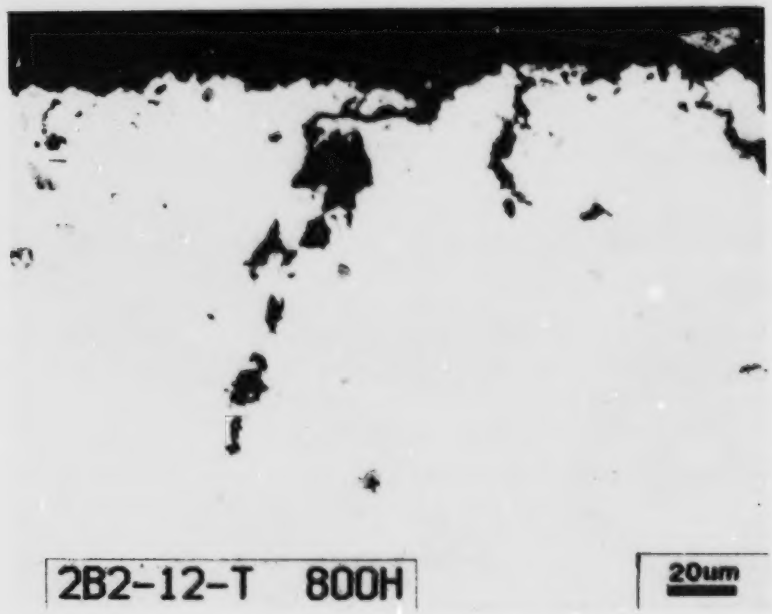
Type of Attack:

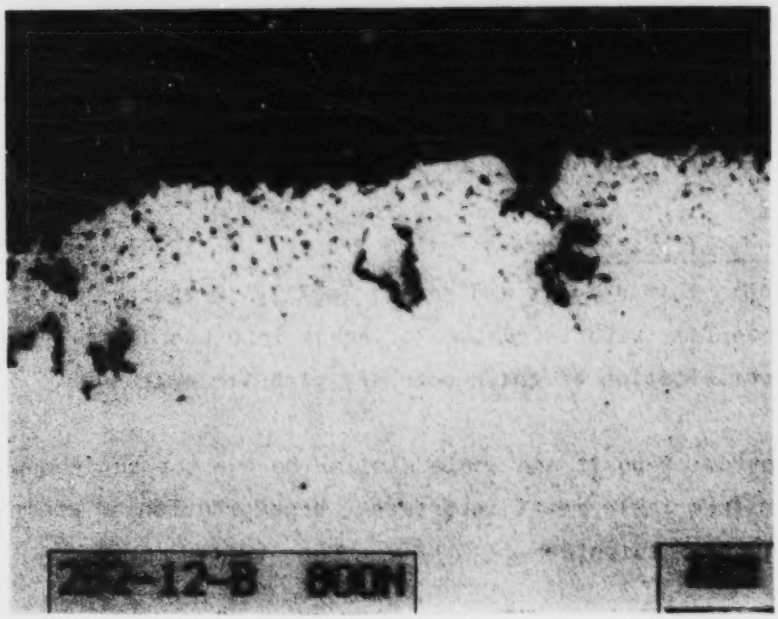
Top: Thin deposit and scale; relatively planar scale/metal interface; local areas of intrusions of scale and precipitation of globular sulphides.

Bottom: Thick multi-layered deposit and scale; precipitation of fine grain-boundary globular sulphides.

Other Comments:

Deposits are much thicker at the bottom than at the top of the coupon.





Photomicrographs of coupon 12 (800H), probe 2B2.
Top photo - position 8; bottom photo - position 3.8.

PROBE: 2B2 COUPON: 13 ALLOY: 304H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 700 C

Bottom : 672 C

Position	1	2	3	4	5	6	7	8
Metal Loss	50	30	25	35	60	60	30	25
Internal Pen.	55	60	50	20	20	80	70	45
Scale	15	20	TR	25	15	20	15	15
Deposit	25	270	--	150	30	340	80	25
Bore Scale	20	15	20	15	20	20	25	20

Hardness - Before Exposure: 80 RB

After - Top: 79.5 80.9

Bottom: 71.0 80.3

Coupon Description:

Top: Polished, uniform, black scale/deposit, punch-mark visible.

Bottom: Eroded appearing, black multi-layered scale/deposit. Spalled over a large area to intermediate tan or brown layers and to the alloy surface.

Type of Attack:

Top: Thin deposit and scale, locally irregular scale/metal interface with intrusions of scale into the alloy. Internal precipitation of grain-boundary globular sulphides.

Bottom: Deposit and scale similar to the top but somewhat less uniform scale/metal interface. Precipitation of grain-boundary globular sulphides.

Other Comments:

There appears to be grain-boundary precipitates throughout the alloy.

Photomicrographs of coupon 13 (304H), probe 2B2.
Top photo - position 8; bottom photo - position 3.9.

PROBE: 2B2 COUPON: 14 ALLOY: 347H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 700 C

Bottom : 676 C

Position	1	2	3	4	5	6	7	8
Metal Loss	105	30	45	25	35	40	40	40
Internal Pen.	85	40	25	20	40	50	40	55
Scale	20	15	20	20	35	20	15	15
Deposit	30	120	200	60	110	350	40	30
Bore Scale	15	20	35	40	15	30	20	20

Hardness - Before Exposure: 81 RB

After - Top: 80.0 79.0

Bottom: 82.0 82.0

Coupon Description:

Top: Polished, uniform, black scale/deposit. Punchmark visible, minor spalling to the alloy.

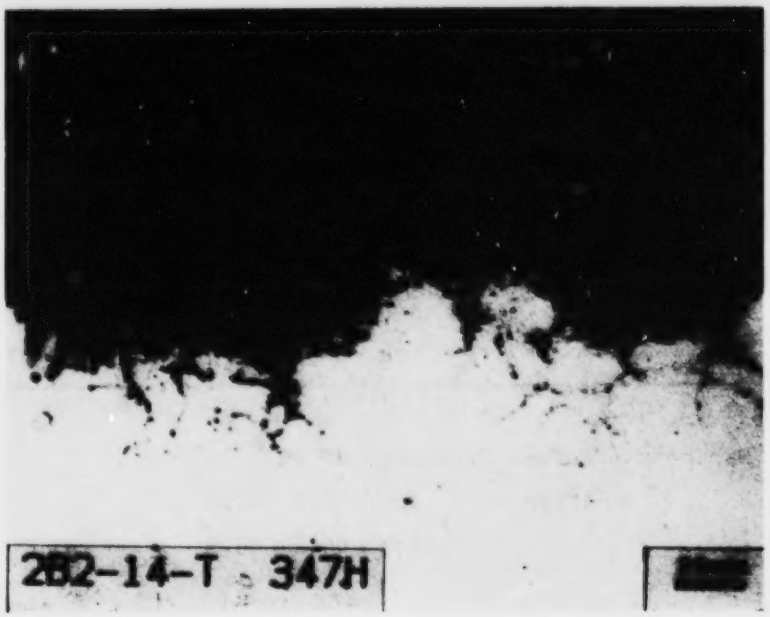
Bottom: Multi-layered, black scale/deposit. Spalled from much of the surface to intermediate tan/pink or brown layers and to the alloy.

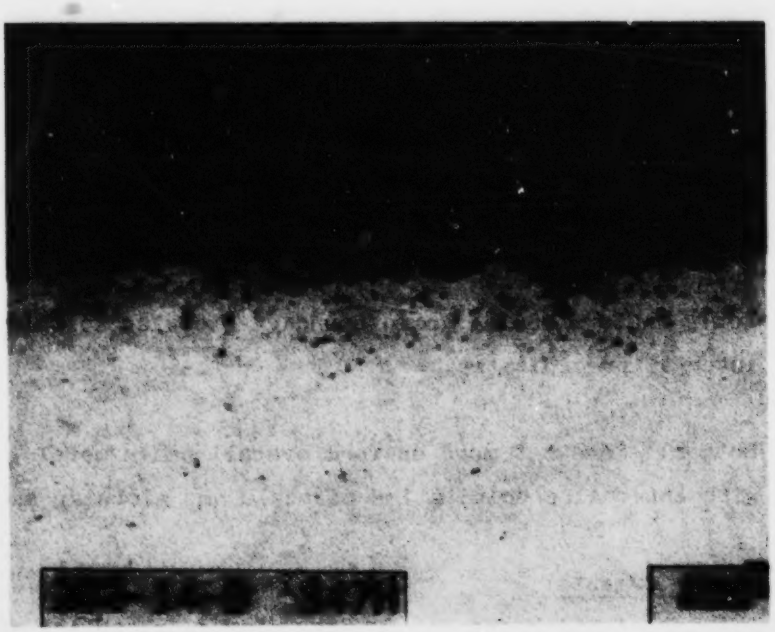
Type of Attack:

Top: Thin scale and deposit, very irregular scale/metal interface with intrusions of scale into the alloy. Precipitation of globular sulphides in a surface or grain-boundary zone.

Other Comments:

Grain-boundary precipitates throughout alloy.





Photomicrographs of coupon 14 (347H), probe 2B2.
Top photo - position 1.1; bottom photo - position 4.3.

PROBE: 2B2 COUPON: 15 ALLOY: 310

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 700 C

Bottom : 680 C

Position	1	2	3	4	5	6	7	8
Metal Loss	50	50	30	25	35	25	10	15
Internal Pen.	75	80	70	100	100	95	80	65
Scale	50	50	45	45	50	40	40	20
Deposit	100	450	400	640	500	430	70	40
Bore Scale	TR	TR	TR	TR	TR	TR	TR	TR

Hardness - Before Exposure: 82 RB

After - Top: 90.8 90.6

Bottom: 89.2 89.5

Coupon Description:

Top: Polished, uniform, black scale/deposit. Punchmark visible. Some spalling to the alloy surface, especially on the east side.

Bottom: Relatively thick, polished, black scale/deposit spalled to the alloy surface, especially on the east side.

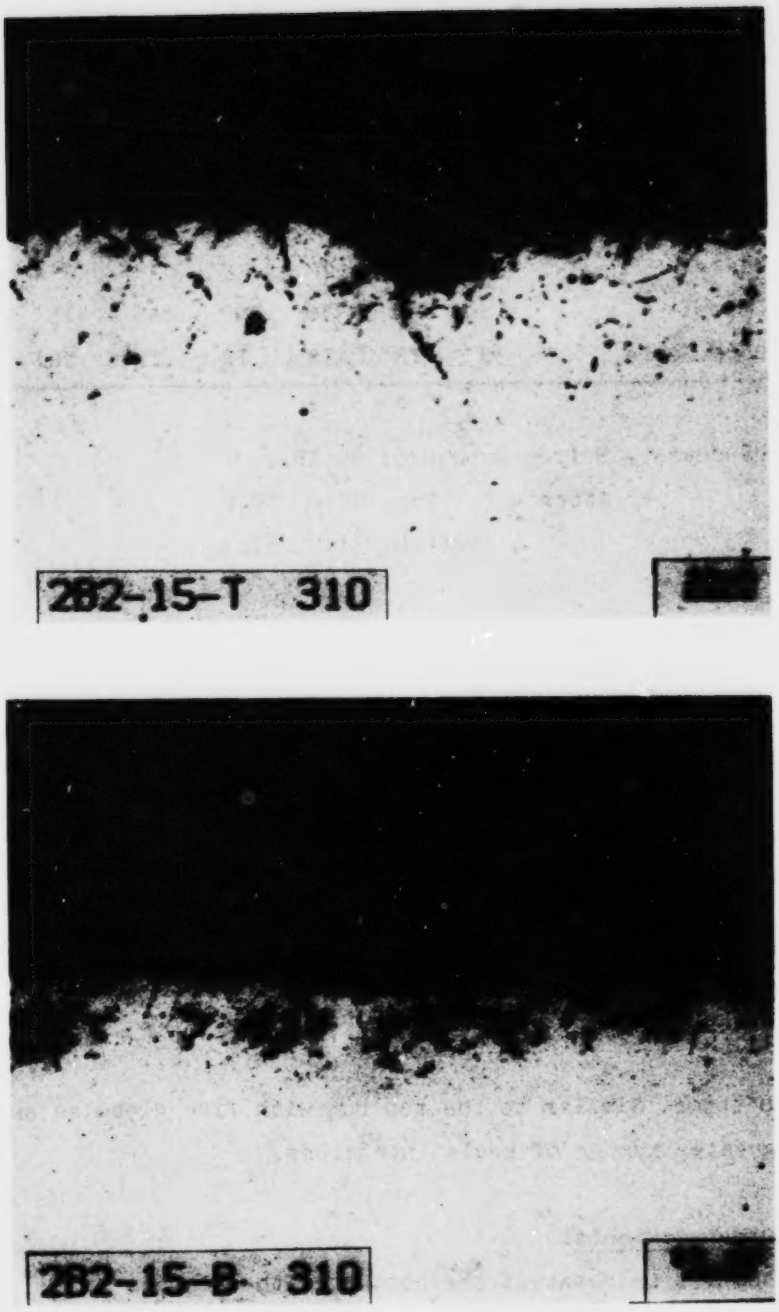
Type of Attack:

Top: Uniform scale; grain-boundary globular sulphides and other internal precipitates.

Bottom: Somewhat more uniform overall scale/metal interface but with internal precipitation of scale and globular sulphides.

Other Comments:

Patches of thick deposit in many places around the specimen. Grain-boundary precipitates throughout the alloy.



Photomicrographs of coupon 15 (310), probe 2B2.
Top photo - position 8; bottom photo - position 3.8.

PROBE: 2B2 COUPON: 16 ALLOY: 800H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 699 C

Bottom : 683 C

Position	1	2	3	4	5	6	7	8
Metal Loss	35	5	10	20	15	35	20	20
Internal Pen.	90	25	10	90	135	95	115	105
Scale	25	30	20	35	25	25	25	20
Deposit	15	430	370	590	845	415	70	20
Bore Scale	30	TR	TR	TR	TR	TR	TR	40

Hardness - Before Exposure: 69 RB

After - Top: 80.0 79.0

Bottom: 81.0 81.1

Coupon Description:

Top: Polished, uniformly thin, black scale/deposit. Punchmark visible. some spalling to the alloy on the west side.

Bottom: Polished, thick, eroded-appearing scale/deposit. Spalled and/or chipped at edge of coupon.

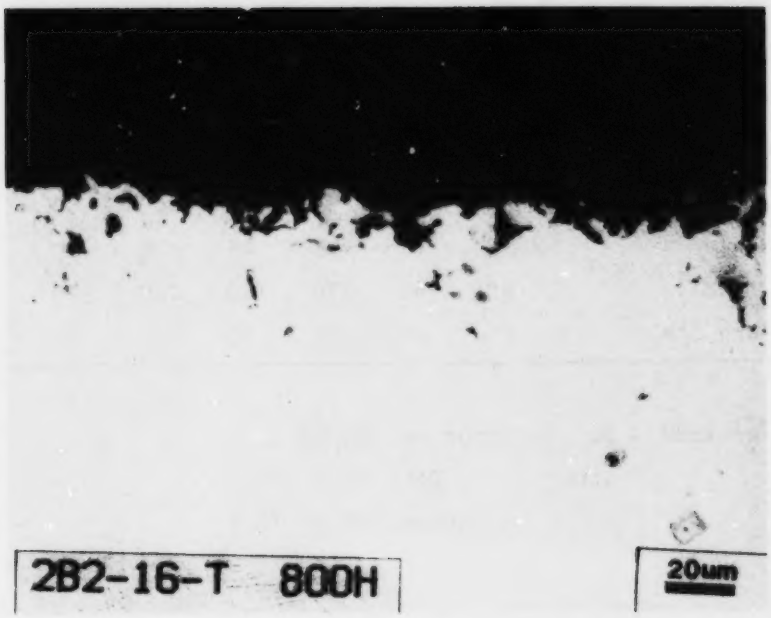
Type of Attack:

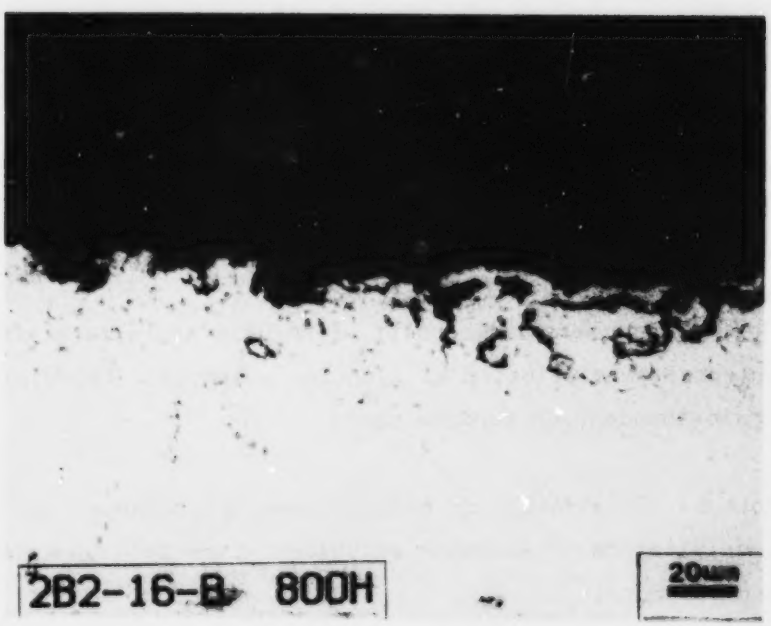
Top: Thin deposit; intrusions of scale into alloy; a few relatively large globular sulphides.

Bottom: Similar to the top but with fine globular sulphides and a greater number of scale intrusions.

Other Comments:

Deposit thickest of the bottom of the coupon.





Photomicrographs of coupon 16 (800H), probe 2B2.
Top photo - position 8; bottom photo - position 3.7.

PROBE: 2B2 COUPON: 17 ALLOY: 304H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 699 C

Bottom : 687 C

Position	1	2	3	4	5	6	7	8
Metal Loss	20	30	30	60	115	75	35	25
Internal Pen.	45	40	55	50	60	50	55	35
Scale	10	TR	15	25	25	25	--	10
Deposit	60	80	570	110	200	310	140	60
Bore Scale	25	15	20	20	35	35	30	35

Hardness - Before Exposure: 80 RB

After - Top: 77.0 78.3

Bottom: 78.4 78.8

Coupon Description:

Top: Polished, uniformly thin, black scale/deposit. Punchmark visible. Minor chipping at edge of coupon.

Bottom: Polished, black scale/deposit. Thinner than on coupon 16. Chipped at edge with coupon 16. Thicker deposit on sides, especially east side.

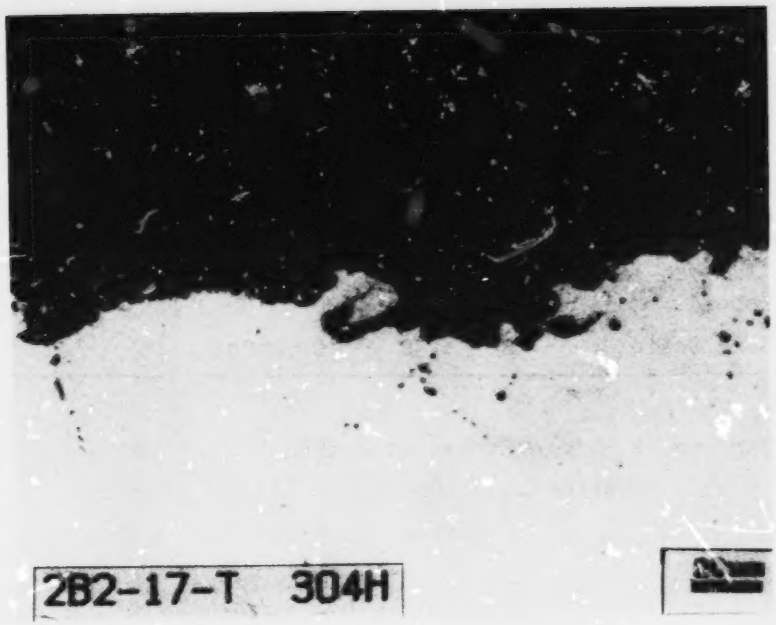
Type of Attack:

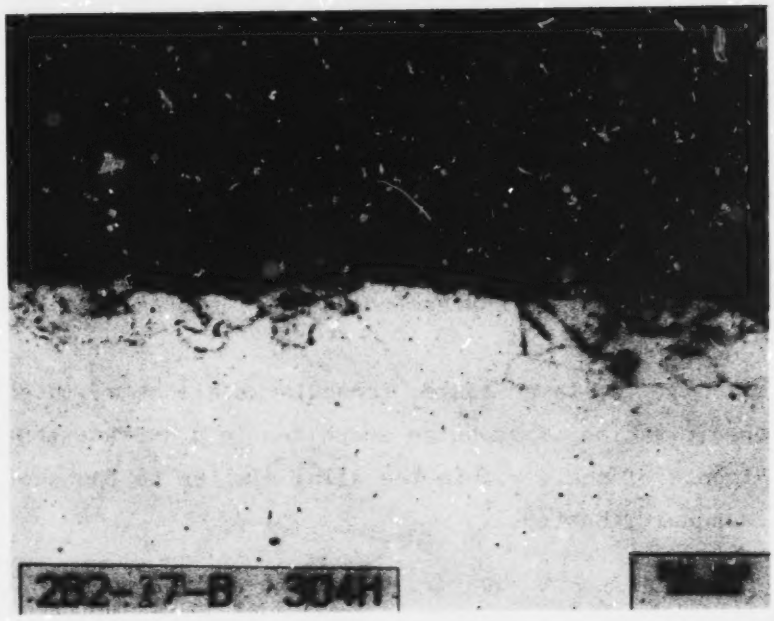
Top: Thin scale and deposit, irregular scale/metal interface; internal precipitation of globular sulphides, especially in a grain-boundary or surface zone.

Bottom: Penetration of scale at grain boundaries and internal precipitation of globular sulphides at grain boundaries and in a surface zone.

Other Comments:

There appears to be grain-boundary precipitates throughout the alloy.





Photomicrographs of coupon 17 (304H), probe 2B2.
Top photo - position 0.2; bottom photo - position 4.

PROBE: 2B2 COUPON: 18 ALLOY: 347H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 699 C

Bottom : 691 C

Position	1	2	3	4	5	6	7	8
Metal Loss	35	35	20	50	95	35	20	25
Internal Pen.	25	30	35	15	25	35	40	20
Scale	TR	10	10	15	35	15	10	10
Deposit	90	280	400	85	140	505	145	50
Bore Scale	20	30	20	20	15	55	30	30

Hardness - Before Exposure: 81 RB

After - Top: 83.1 83.0

Bottom: 82.7 83.8

Coupon Description:

Top: Polished, uniform, thin black scale/deposit. Thicker deposit on east side.

Bottom: Somewhat polished, black scale/deposit.

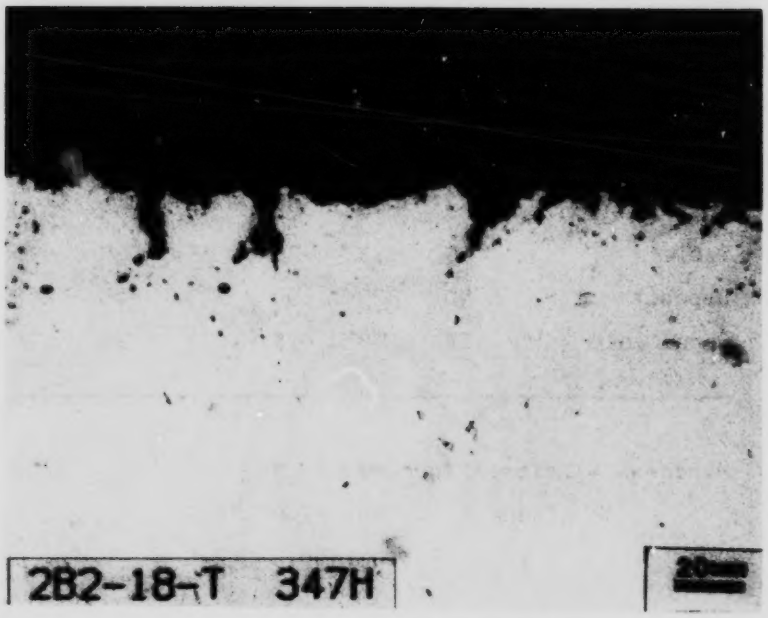
Type of Attack:

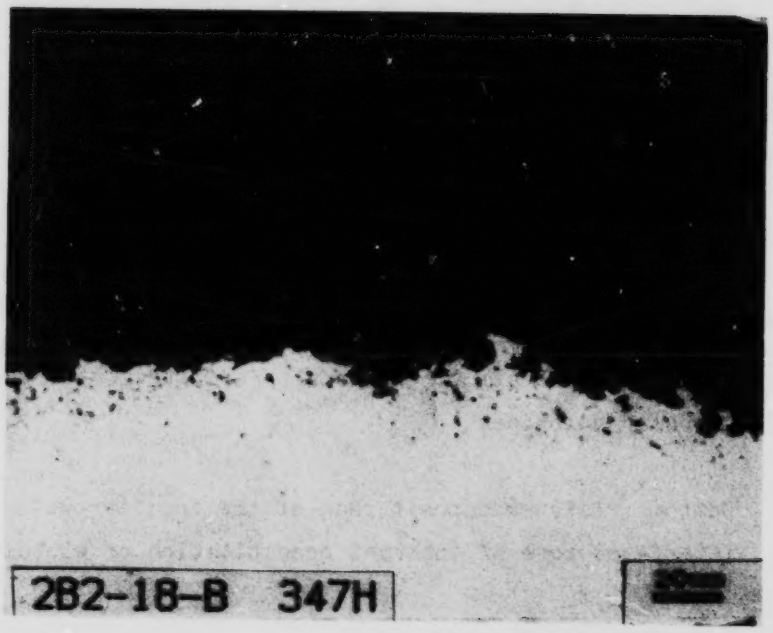
Top: Generally planar scale/metal interface with intrusions of scale into the alloy. Precipitation of globular sulphides in a grain-boundary or surface zone.

Bottom: Two layer scale, irregular scale/metal interface; internal precipitation of globular sulphides in a surface zone. A leading "front" of scale within the alloy similar to the photomicrograph for coupon 10, bottom.

Other Comments:

Patches of very think deposit on the sides of the coupon.





Photomicrographs of coupon 18 (347H), probe 2B2.
Top photo - position 7.5; bottom photo - position 4.

PROBE: 2B2 COUPON: 19 ALLOY: 310

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 699 C

Bottom : 695 C

Position	1	2	3	4	5	6	7	8
Metal Loss	10	5	15	25	20	15	10	--
Internal Pen.	40	55	25	40	60	70	70	60
Scale	15	20	25	25	25	30	35	20
Deposit	40	325	190	135	985	265	55	60
Bore Scale	TR	TR	TR	TR	TR	TR	TR	TR

Hardness - Before Exposure: 82 RB

After - Top: 87.0 88.9

Bottom: 88.2 89.0

Coupon Description:

Top: Polished, thin, scale/deposit; black at joint with 18, reddish/black at 20. Previously spalled areas; spalled to alloy.

Bottom: Somewhat polished, brown/black scale/deposit. Textured surface.

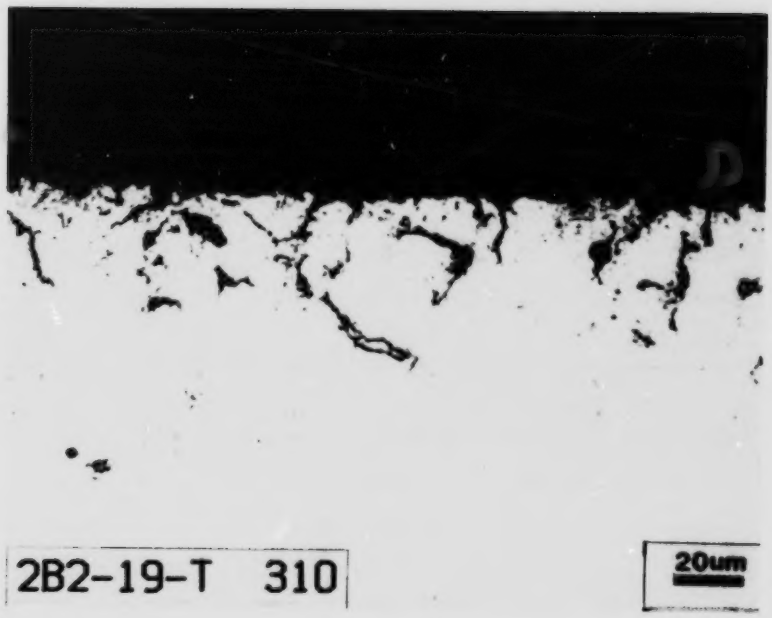
Type of Attack:

Top: Generally planar scale/metal interface with intrusions of scale into the alloy. Internal precipitation of grain-boundary globular sulphides

Bottom: Thicker deposit than at the top; irregular scale/metal interface; zone of internal precipitation of globular sulphides.

Other Comments:

Deposit is thickest at the bottom.



Photomicrographs of coupon 19 (310), probe 2B2.
Top photo - position 8; bottom photo - position 4.

PROBE: 2B2 COUPON: 20 ALLOY: 800H

EXPOSURE: 5000 h RUNS: 5 - 6 - 7 - 8 - 9

Estimated average temperature - Top : 699 C

Bottom : 699 C

Position	1	2	3	4	5	6	7	8
Metal Loss	15	10	20	25	15	10	10	10
Internal Pen.	65	35	25	35	35	40	85	25
Scale	10	15	15	15	30	25	10	15
Deposit	20	125	20	15	805	340	65	25
Bore Scale	--	--	TR	--	--	--	--	--

Hardness - Before Exposure: 69 RB

After - Top: 79.0 80.5

Bottom: 82.0 81.7

Coupon Description:

Top: Polished, thin, red/black scale/deposit, punchmark visible. Spalled on sides to alloy.

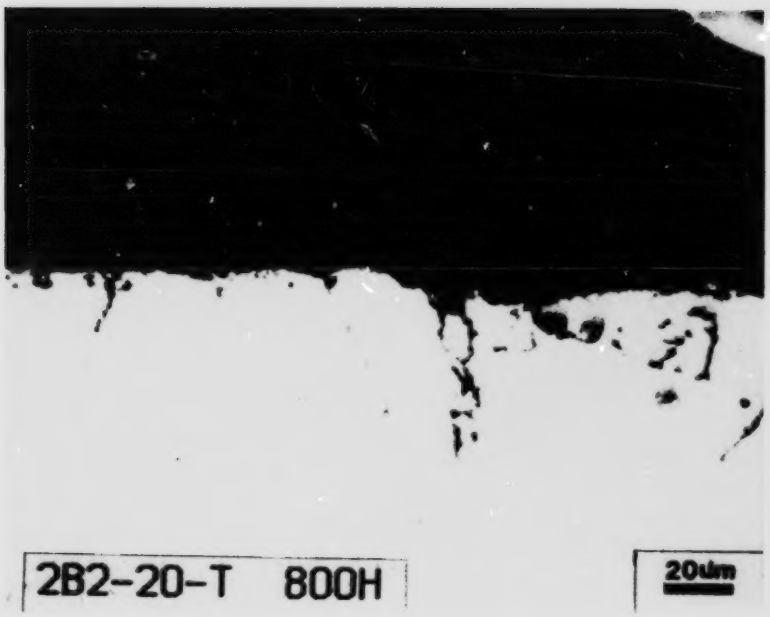
Bottom: Thin brown/black scale/deposit; spalled in small areas to a grey scale.

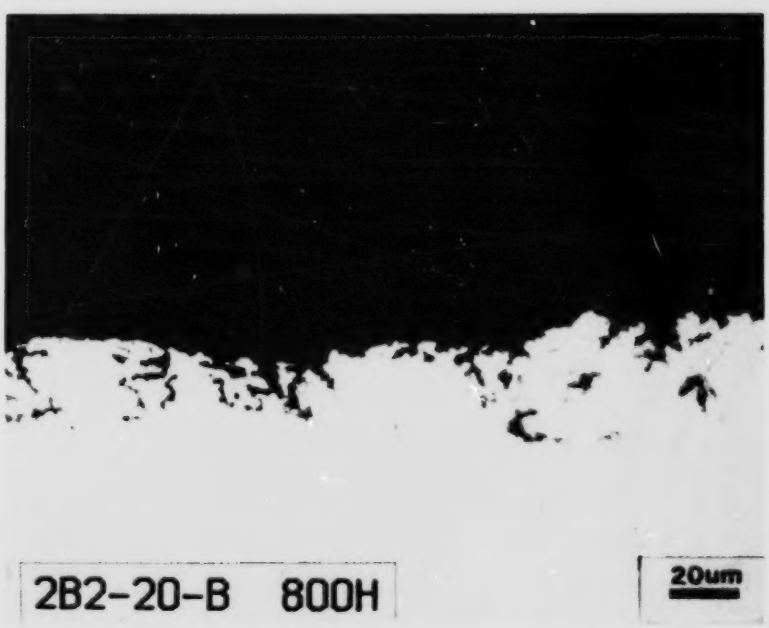
Type of Attack: ,

Top: Planar scale/metal interface with occasional scale intrusions, a few grain-boundary globular sulphides.

Bottom: Thick deposit, wavy scale/metal interface with the interface becoming diffuse in some areas. Internal precipitation of oxides and a few globular sulphides.

Other Comments:





Photomicrographs of coupon 20 (800H), probe 2B2.
Top photo - position 0.1; bottom photo - position 4.

PMRL 86-39 (TR)

APPENDIX 2

DATA SHEETS AND PHOTOMICROGRAPHS

OF

PROBE 4B1

8000-h EXPOSURE

RUNS 2, 3, 4, 5, 6, 7, 8 AND 9

PROBE: 4B1 COUPON: 1 ALLOY: 304H/N82/T91

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 621 C

Bottom : 503 C

Position	4				8		
	304H	N82	T91		304H	N82	T91
Metal Loss	860	795	661		10	30	160
Internal Pen.	55	--	--		--	--	--
Scale	--	--	10		20	TR	115
Deposit	--	--	--		--	--	--
Bore Scale	--	40	20		--	--	55

Hardness - Before Exposure:

After - Top:

Bottom:

Coupon Description:

Top: Uniform, matt, black/brown scale/deposit. Weld visible by slight difference in colour and texture of the scale/deposit. Deposit surface on 304H slightly textured.

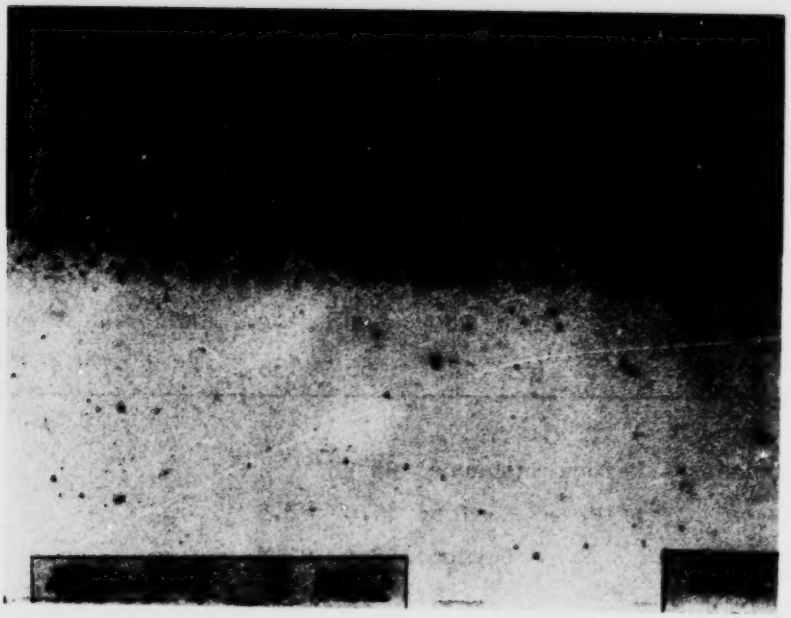
Bottom: Weld visible; smooth black scale/deposit; significant metal loss from 304H and N82 relative to T91 and the 304H extension.

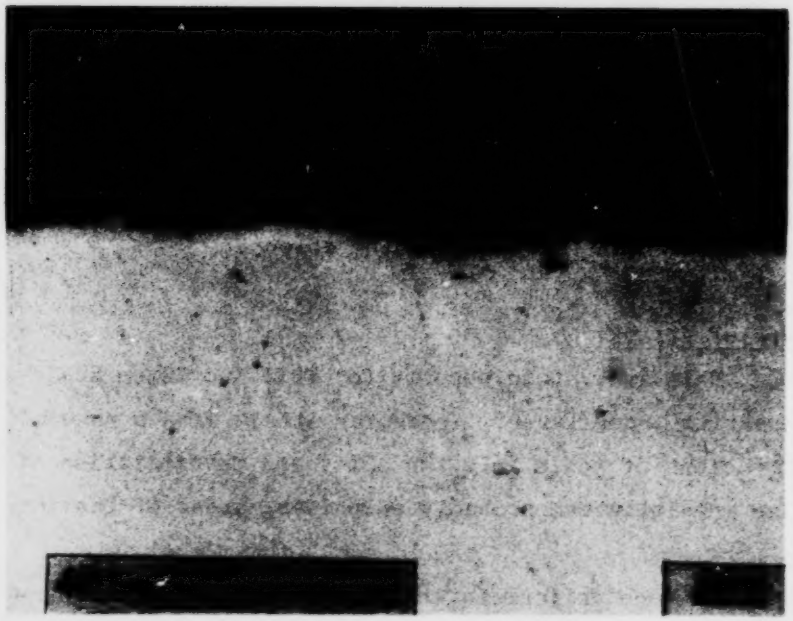
Type of Attack:

Top: N82 - Thin scale containing particles of alloy; uniform zone of internal precipitation of very fine globular precipitates, probably sulphides.

Bottom: N82 - Remnants of scale only, no obvious internal precipitation.

Other Comments:





Photomicrographs of coupon 1 (N82), probe 4B1.
Top photo - position 8; bottom photo - position 4.

PROBE: 4B1 COUPON: 2 ALLOY: T91

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 621 C

Bottom : 518 C

Position	1	2	3	4	5	6	7	8
Metal Loss	180	170	165	170	190	115	205	165
Internal Pen.	TR	TR	10	TR	TR	TR	TR	TR
Scale	145	115	90	45	85	55	115	180
Deposit	15	380	500	390	540	940	90	40
Bore Scale	65	75	55	35	45	70	65	65

Hardness - Before Exposure: 93 RB

After - Top: 85.0 87.5

Bottom: 93.0 93.0

Coupon Description:

Top: Uniform, dark brown/black deposit with a few areas of prior spalling near position 1. Deposit seems thicker toward coupon 3.

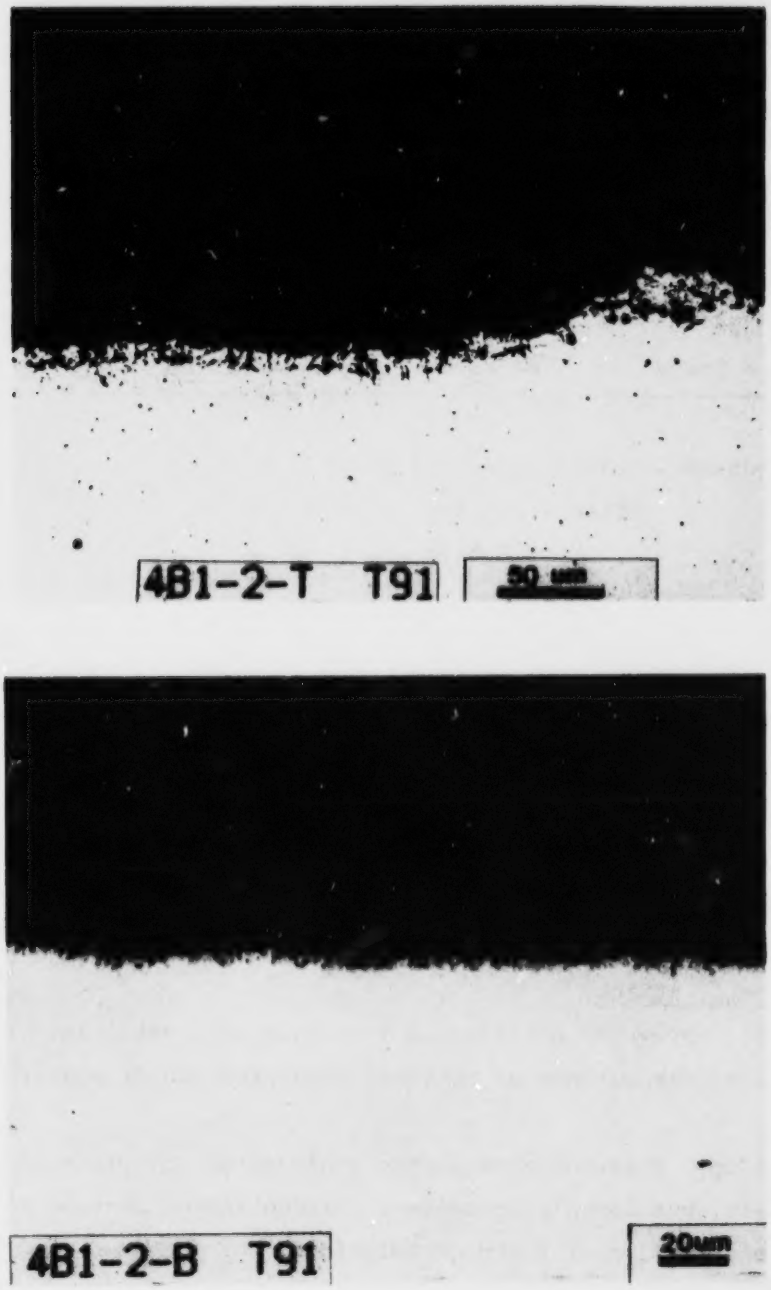
Bottom: Thick, non uniform black deposit. A thermocouple well was very close to the bottom of this probe and the thickness and location of the deposit reflect this. The thicker areas of deposit have a rough surface and lighter colour.

Type of Attack:

Top: Relatively thin deposit for T91; two layer scale with a porous appearing inner layer. Irregular attack with a zone of very fine intrusions of scale into the alloy and precipitation of extremely fine precipitates, probably sulphides, ahead of the intrusions.

Bottom: More uniform interface, more dense appearing scale. Narrow zone of internal precipitation from the scale/metal interface.

Other Comments:



Photomicrographs of coupon 2 (T91), probe 4B1.
Top photo - position 8; bottom photo - position 4.

PROBE: 4B1 COUPON: 3 ALLOY: 304H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 621 C

Bottom : 534 C

Position	1	2	3	4	5	6	7	8
Metal Loss	35	35	95	230	210	35	30	35
Internal Pen.	25	15	TR	TR	TR	20	30	30
Scale	25	--	20	10	15	30	30	35
Deposit	115	--	--	--	--	50	135	25
Bore Scale	--	--	--	--	--	--	--	--

Hardness - Before Exposure: 80 RB

After - Top: 83.0 81.6

Bottom: 79.1 79.0

Coupon Description:

Top: Uniform, smooth, dark brown deposit; some spalling (chipping) at edge with coupon 2.

Bottom: Similar to top but scale/deposit appears to be thinner in one area toward coupon 4. Well defined transition between the top and bottom at position 2 and 6.

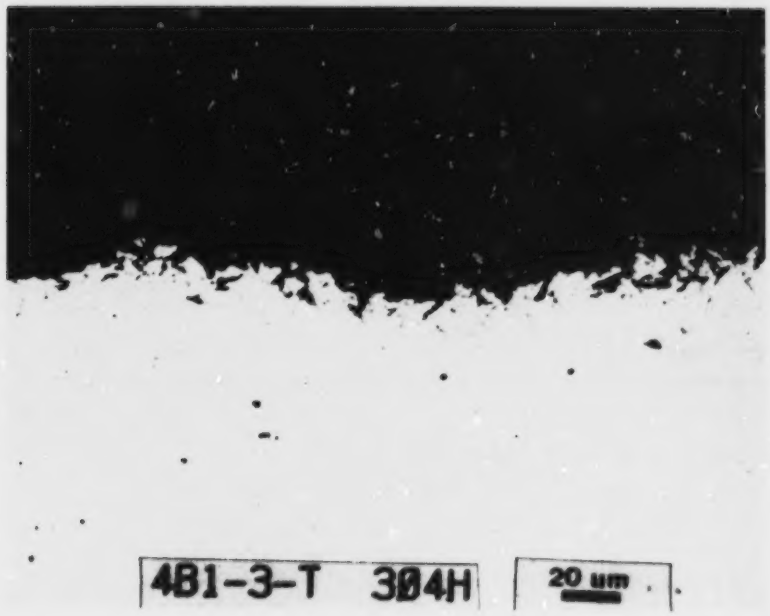
Type of Attack:

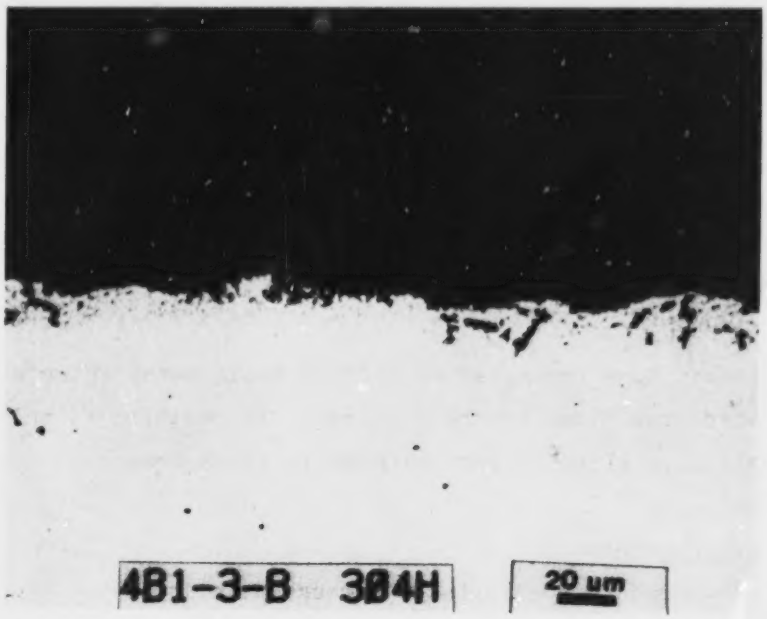
Top: Irregular scale/metal interface with small intrusions of scale; narrow zone of internal precipitation of globular sulphides.

Bottom: Somewhat more planar scale/metal interface on a macro scale, but locally irregular. Discontinuous surface zone of precipitation of globular sulphides.

Other Comments:

Precipitates at grain boundaries and slip bands throughout the alloy.





Photomicrographs of coupon 3 (304H), probe 4B1.
Top photo - position 8; bottom photo - position 5-6.

PROBE: 4B1 COUPON: 4 ALLOY: 347H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 621 C

Bottom : 550 C

Position	1	2	3	4	5	6	7	8
Metal Loss	50	45	75	300	285	40	25	35
Internal Pen.	20	35	30	TR	TR	35	30	15
Scale	45	20	35	TR	TR	60	25	35
Deposit	230	155	--	--	--	--	210	95
Bore Scale	15	25	40	20	40	30	30	15

Hardness - Before Exposure: 81 RB

After - Top: 83.8 84.5

Bottom: 84.3 82.5

Coupon Description:

Top: Uniform, dark brown deposit, some chipping at edges.

Bottom: Uniform thin brown/block scale/deposit.

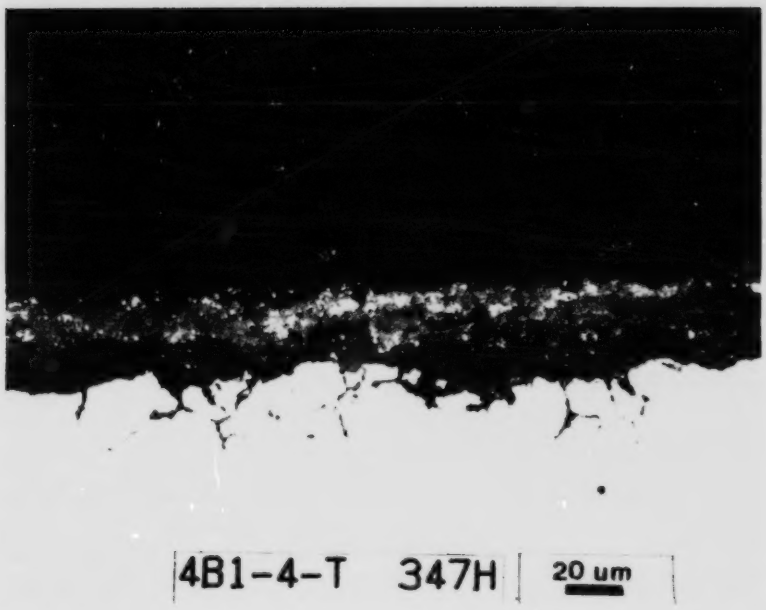
Type of Attack:

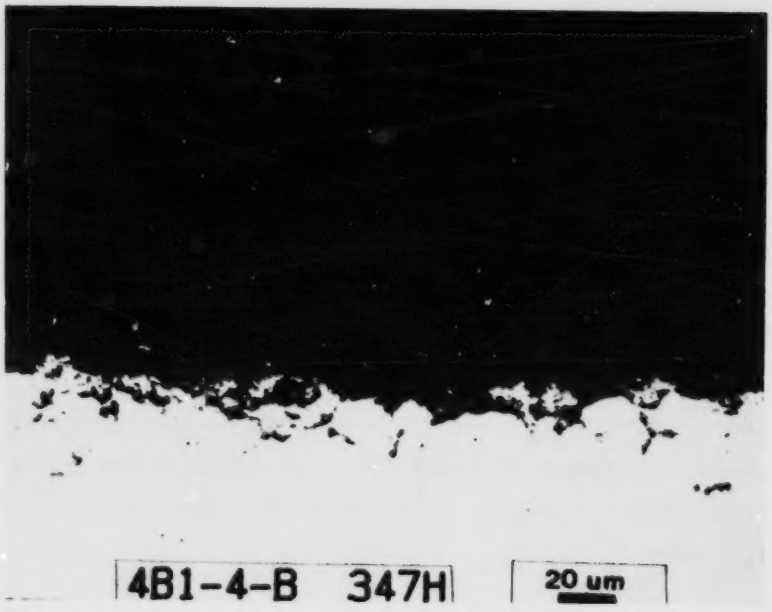
Top: Well defined scale/metal interface with grain-boundary intrusions of scale in some areas; precipitation of very fine grain-boundary globular sulphides.

Bottom: More irregular or diffuse scale/metal interface, especially towards the sides of the specimen. At position 4, only traces of scale with globular precipitates in local areas.

Other Comments:

Grain-boundary precipitates throughout alloy.





Photomicrographs of coupon 4 (347H), probe 4B1.
Top photo - position 7-8; bottom photo - position 3-4.

PROBE: 4B1 COUPON: 5 ALLOY: 310

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 621 C

Bottom : 565 C

Position	1	2	3	4	5	6	7	8
Metal Loss	10	15	60	350	420	20	5	--
Internal Pen.	25	40	45	TR	TR	35	30	20
Scale	25	20	35	TR	--	25	25	15
Deposit	500	950	--	--	--	1010	550	390
Bore Scale	--	--	TR	--	TR	TR	--	--

Hardness - Before Exposure: 82 RB

After - Top: 89.2 87.5

Bottom: 84.1 84.5

Coupon Description:

Top: Brown deposit, some spalling to a black scale/deposit layer. Some spalling to the alloy at position 2 at the transition from top to bottom.

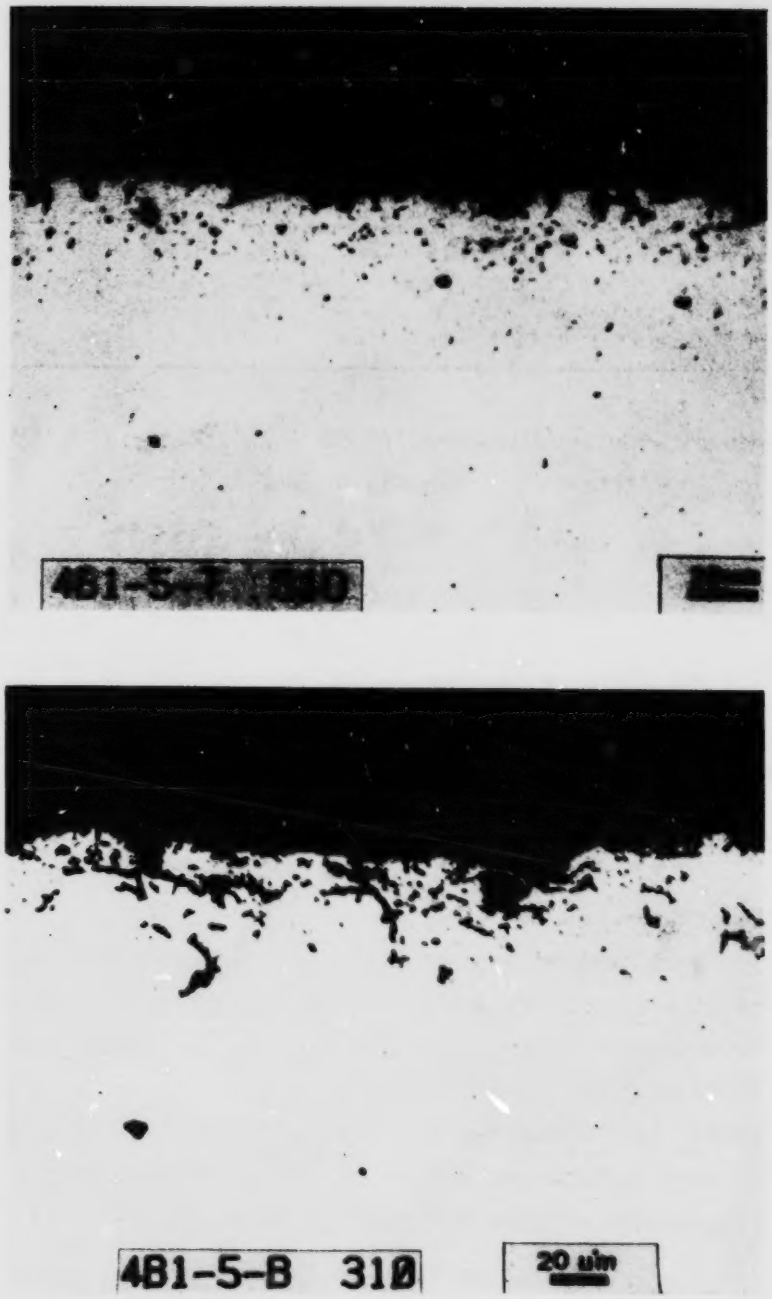
Bottom: Uniform brown/Black thin scale/deposit.

Type of Attack:

Top: Well defined scale/metal interface with a few minor scale intrusions. A few globular sulphides.

Bottom: More intrusions of scale than at top; precipitation of globular sulphides to about the same depth as the scale intrusions. At position 4, a nearly continuous thin zone of precipitation of sulphides.

Other Comments:



Photomicrographs of coupon 5 (310), probe 4B1.
Top photo - position 7; bottom photo - position 3.

PROBE: 4B1 COUPON: 6 ALLOY: 800H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 622 C

Bottom : 581 C

Position	1	2	3	4	5	6	7	8
Metal Loss	25	415	470	370	30	25	5	20
Internal Pen.	95	15	10	20	80	50	60	80
Scale	15	15	--	15	15	20	15	30
Deposit	465	--	--	--	570	300	995	720
Bore Scale	TR	TR	--	--	--	TR	TR	--

Hardness - Before Exposure: 69 RB

After - Top: 83.0 84.5

Bottom: 81.6 81.3

Coupon Description:

Top: Dark brown deposit of varying thickness that appears to be the result of previous spalling. A few small areas spalled to the alloy surface.

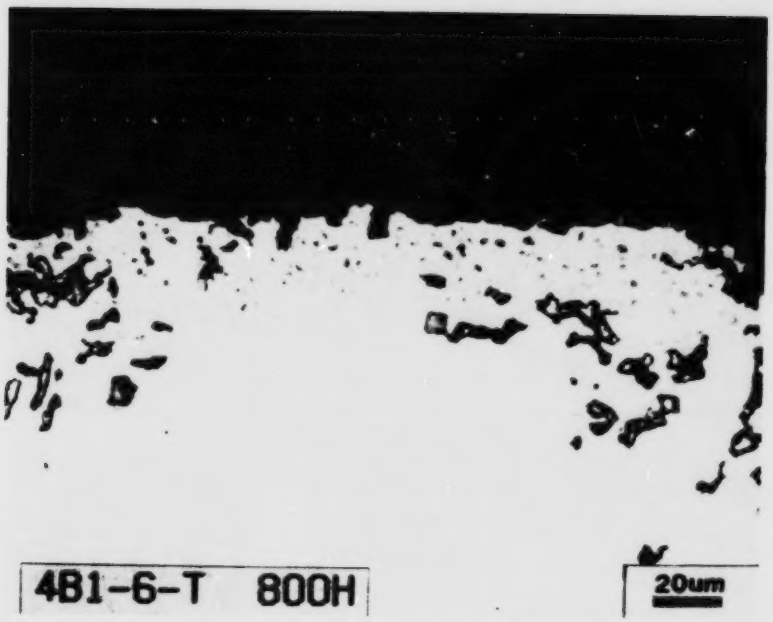
Bottom: Smooth thin, brown/black scale/deposit.

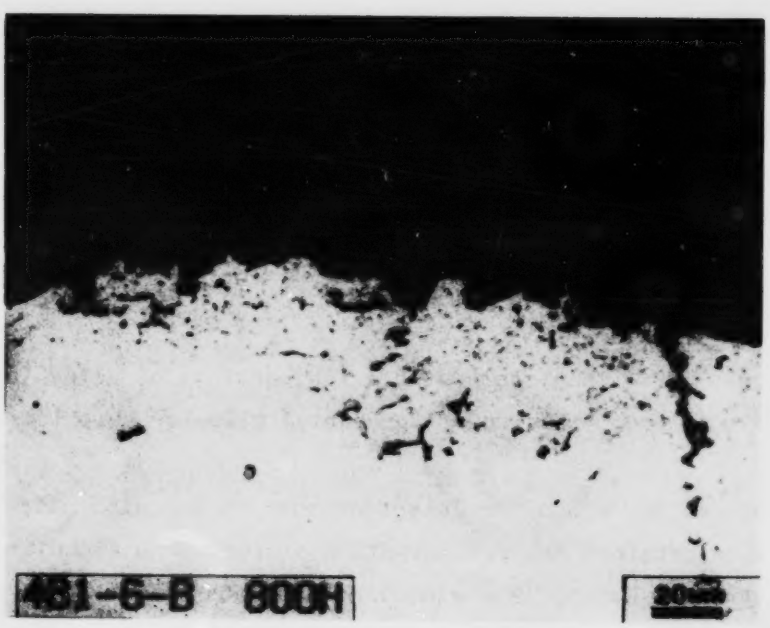
Type of Attack:

Top: Well defined deposit/scale and scale/metal interface; narrow zone of precipitation of (probably) globular sulphides and precipitation of other sulphides/oxides to a greater depth.

Bottom: Poorly defined scale/metal interface with precipitation of very fine globular sulphides in a well defined surface zone and precipitation of other oxides /sulphides.

Other Comments:





Photomicrographs of coupon 6 (800H), probe 4B1.
Top photo - position 0.5; bottom photo - position 4.1.

PROBE: 4B1 COUPON: 7 ALLOY: 304H/N82/T91

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 622 C

Bottom : 596 C

Position	4				8		
	304H	N82	T91		304H	N82	T91
Metal Loss	370	950	555		5	110	155
Internal Pen.	--	145	15		50	40	40
Scale	TR	--	140		30	TR	50
Deposit	--	--	--		170	460	660
Bore Scale	TR	55	280		TR	85	260

Hardness - Before Exposure:

After - Top:

Bottom:

Coupon Description:

Top: 304H and N82 - Dark brown deposit; black sublayer; previously spalled areas. T91 - thick, multi-layered scale/ deposit. Deposit appears to have repeatedly spalled and reformed. Deposits over 1 mm thick in some locations.

Bottom: Weld appears receded more than 304H or T91. Smooth, brown/ black scale/deposit. Some indications of prior spalling on T91.

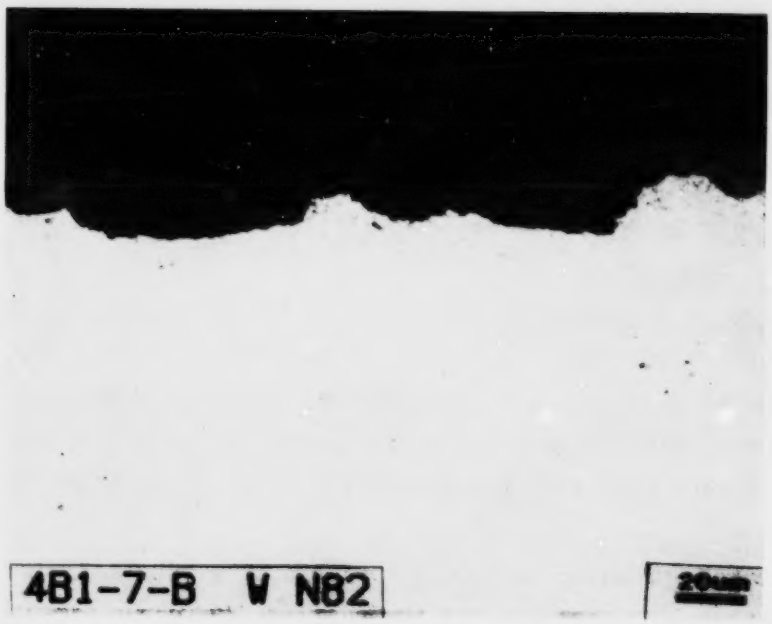
Type of Attack:

Top: N82 - Thin scale with a few particle of alloy in the scale. Zone of precipitation of (probably) globular sulphides.

Bottom: N82 - Rougher interface than at top with only remnants of scale retained and precipitation of very fine globular sulphides to a greater depth. The globular sulphides appear to be in a continuous, or nearly continuous, surface zone.

Other Comments:

Weld root crack at position 4; lack of fusion and porosity at position 8.



Photomicrographs of coupon 7 (N82), probe 4B1.
Top photo - position 8; bottom photo - position 4.

PROBE: 4B1 COUPON: 8 ALLOY: T91

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 622 C

Bottom : 612 C

Position	1	2	3	4	5	6	7	8
Metal Loss	105	135	310	385	400	145	140	90
Internal Pen.	15	15	10	TR	TR	10	15	15
Scale	70	85	140	140	160	150	75	60
Deposit	1290	310	60	--	--	2500	2540	620
Bore Scale	80	120	100	100	115	105	90	90

Hardness - Before Exposure: 93 RB

After - Top: 89.8 88.2

Bottom: 91.1 92.9

Coupon Description:

Top: Very thick (>1 mm), non-uniform scale/deposit. Many previously spalled areas; underlying layers are various colours; black, brown, red.

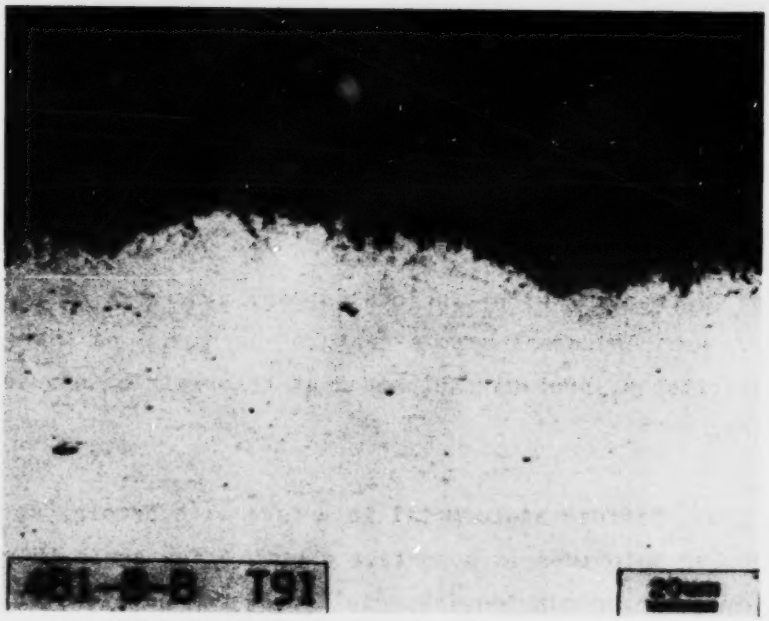
Bottom: Brown/black scale/deposit; some prior spalling, but now a generally smooth surface. Deposits are thicker toward coupon 9.

Type of Attack:

Top: Multi-layer scale with a well defined inner layer/film next to the metal. Locally macroscopically irregular scale/metal interface. Narrow zone in internal precipitation of both fine scale intrusions and very fine globular precipitates, probably sulphides.

Bottom: Similar to top, but with a more wavy scale/metal interface. Character of the scale is different with the inner layer/film mentioned above not present adjacent to the metal.

Other Comments:



Photomicrographs of coupon 8 (T91), probe 4B1.
Top photo - position 0.8; bottom photo - position 3.9.

PROBE: 4B1 COUPON: 9 ALLOY: 304H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 629 C

Bottom : 627 C

Position	1	2	3	4	5	6	7	8
Metal Loss	45	50	150	320	305	35	20	45
Internal Pen.	60	70	65	15	10	75	55	35
Scale	--	35	40	25	25	15	20	20
Deposit	--	240	--	--	--	370	140	45
Bore Scale	15	--	--	10	55	25	15	--

Hardness - Before Exposure: 80 RB

After - Top: 79.0 79.0

Bottom: 81.5 81.5

Coupon Description:

Top: Dark brown scale/deposit, spalled to metal at coupon 8. Black underlayer. Evidence of prior spalling but surface is now smooth.

Bottom: Apparently thin, adherent, uniform brown/black scale/deposit.

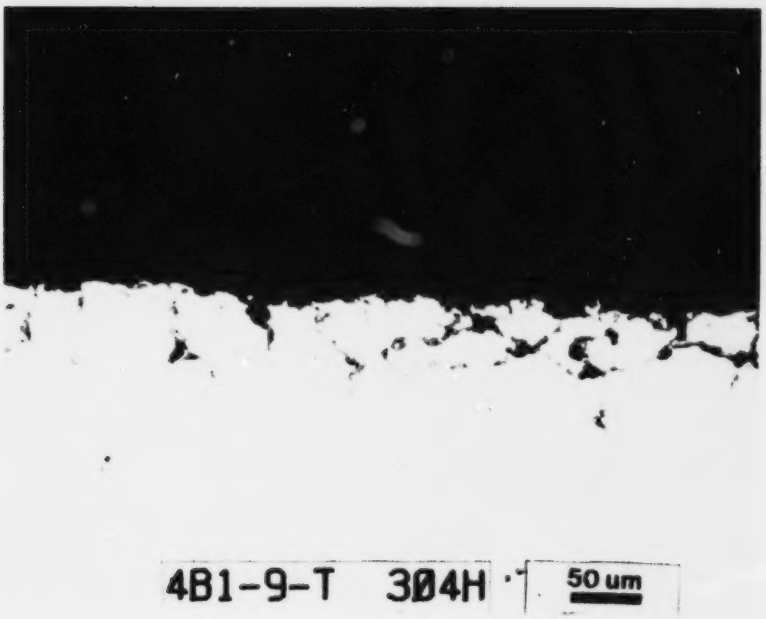
Type of Attack:

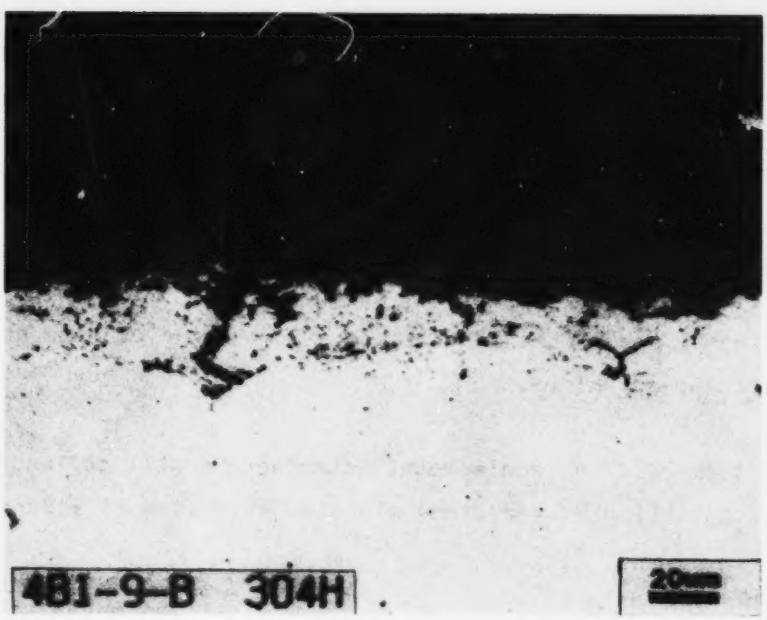
Top: Thin scale with, in local areas, a network of scale at the alloy grain boundaries to a depth of perhaps 3 of 4 grains. Globular precipitates, probably sulphides at the grain boundaries in some areas.

Bottom: Diffuse scale/metal interface with precipitation of globular sulphides in a surface zone. A few scale intrusions at the alloy grain boundaries, especially toward the sides of the section.

Other Comments:

There appears to be grain-boundary precipitates throughout the alloy.





Photomicrographs of coupon 9 (304H), probe 4B1.
Top photo - position 6-7; bottom photo - position 2.9.

PROBE: 4B1 COUPON: 10 ALLOY: 347H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 636 C

Bottom : 641 C

Position	1	2	3	4	5	6	7	8
Metal Loss	55	105	80	245	305	50	70	30
Internal Pen.	40	45	30	30	20	30	30	35
Scale	80	50	55	30	--	--	160	80
Deposit	115	225	--	--	--	--	440	--
Bore Scale	30	45	30	25	20	20	25	15

Hardness - Before Exposure: 81 RB

After - Top: 74.0 81.5

Bottom: 76.0 77.0

Coupon Description:

Top: Thick, dark brown deposit, previously spalled at the side, spalled to metal at position 6.

Bottom: Thin, dark-brown scale/deposit; some "micro" spallation to a grey scale.

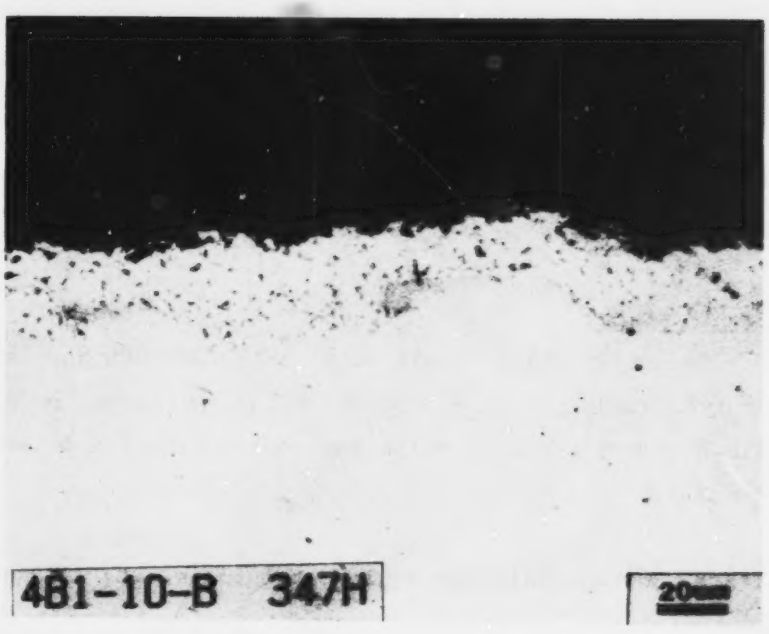
Type of Attack:

Top: Irregular scale metal interface with many intrusions and internal precipitation of scale. Some areas contain grain-boundary globular sulphides.

Bottom: Diffuse scale metal interface; a well defined zone of precipitation of very fine globular sulphides in a surface zone.

Other Comments:

Grain boundary precipitates throughout the alloy.



Photomicrographs of coupon 10 (347H), probe 4B1.
Top photo - position 1-2; bottom photo - position 3.8.

PROBE: 4B1 COUPON: 11 ALLOY: 310

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 644 C

Bottom : 656 C

Position	1	2	3	4	5	6	7	8
Metal Loss	5	115	80	275	290	40	25	10
Internal Pen.	70	70	125	25	20	105	25	45
Scale	40	170	70	50	10	75	40	45
Deposit	145	425	85	--	--	150	630	250
Bore Scale	--	10	TR	15	TR	TR	TR	TR

Hardness - Before Exposure: 82 RB

After - Top: 90.0 89.0

Bottom: 88.5 87.6

Coupon Description:

Top: Thick (in some areas) dark brown scale/deposit. Spalled (previously as well as after removal from combustor) both to intermediate layers (dark-brown, black, grey) and to the metal.

Bottom: Thin, adherent, brown/black scale/deposit; minor micro-or pin-point spalling to a grey scale.

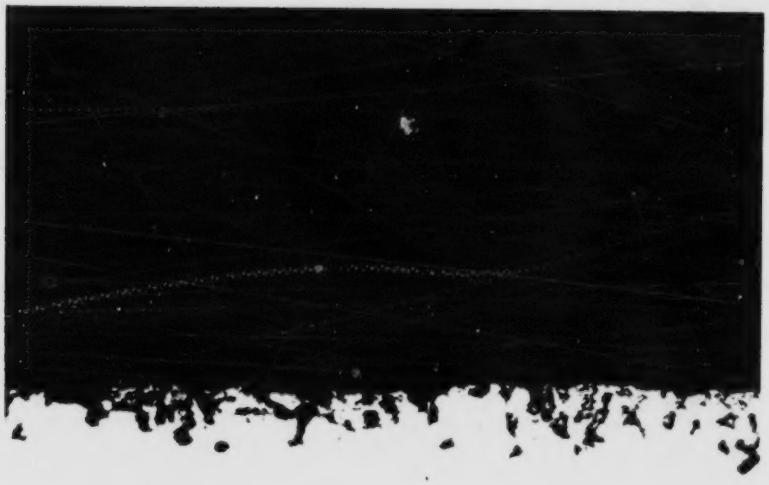
Type of Attack:

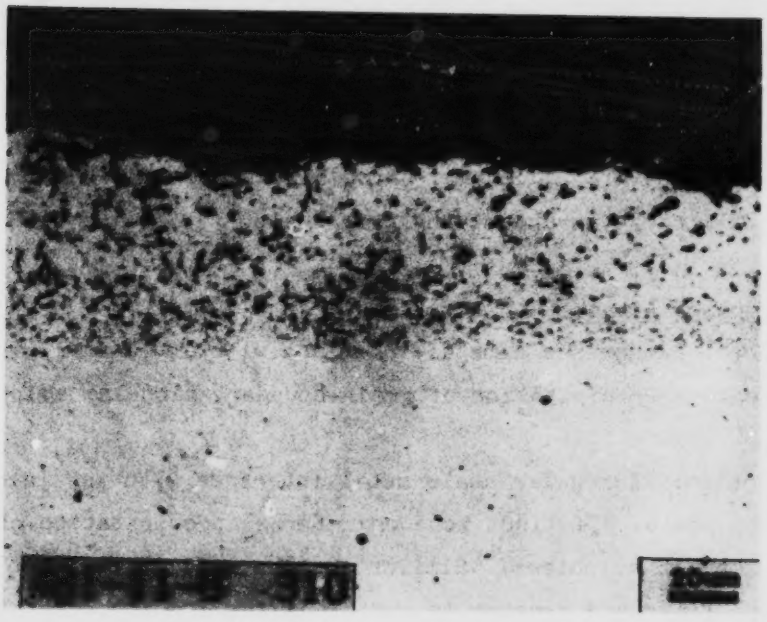
Top: Generally planar scale/metal interface but some areas have many intrusions of scale into the alloy. Internal precipitation of grain-boundary globular sulphides to a somewhat greater depth than the scale.

Bottom: Somewhat diffuse scale/metal interface; well defined zone of internal precipitation of (probably) globular sulphides. The precipitates within this zone are smaller and more numerous at the advancing or leading edge of the zone.

Other Comments:

Precipitates, probably sigma phase, throughout the alloy.





Photomicrographs of coupon 11 (310), probe 4B1.
Top photo - position 7.9; bottom photo - position 4.0.

PROBE: 4B1 COUPON: 12 ALLOY: 800H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 651 C

Bottom : 670 C

Position	1	2	3	4	5	6	7	8
Metal Loss	15	35	105	260	240	40	10	15
Internal Pen.	110	195	290	65	45	130	65	95
Scale	15	45	45	35	25	25	--	20
Deposit	1080	185	165	--	--	550	--	395
Bore Scale	--	TR	25	20	15	TR	--	TR

Hardness - Before Exposure: 69 RB

After - Top: 77.0 77.5

Bottom: 79.0 79.0

Coupon Description:

Top: Areas of thick, dark brown deposit, spalled to the metal surface with intermediate black and brown layers. Spalling is greatest at the sides - positions 2 and 6.

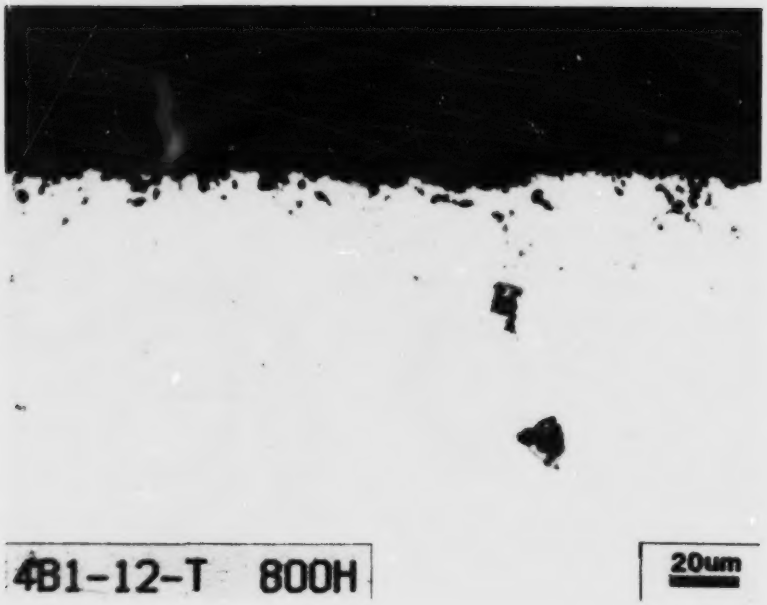
Bottom: Thin, adherent, brown/black deposit with some minor spalling to an underlying grey scale.

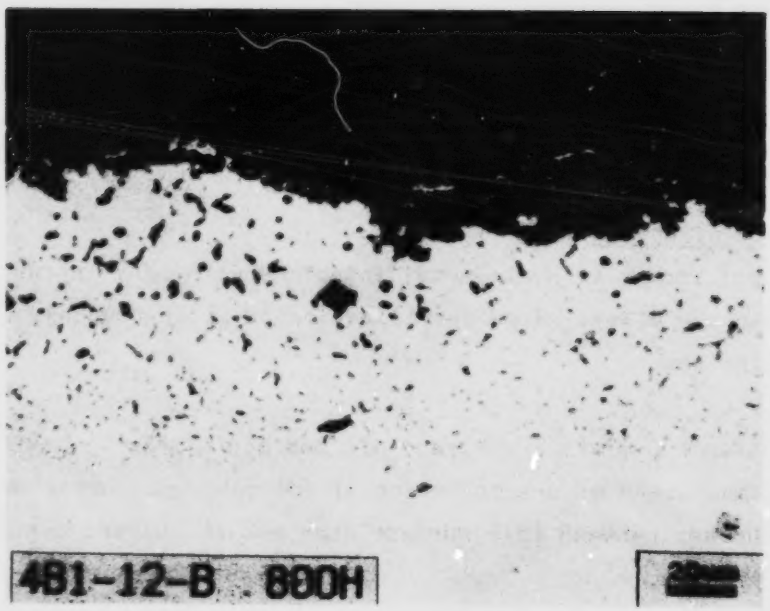
Type of Attack:

Top: Planar scale/metal interface with local small intrusions of scale. Precipitation of grain-boundary globular sulphides.

Bottom: Irregular scale metal interface with particles of alloy in the scale. Distinct zone on internal precipitation of (probably) globular sulphides. Similar to coupon 11 in that the precipitates are finer and greater in number at the leading edge of this zone.

Other Comments:





Photomicrographs of coupon 12 (800H), probe 4B1.
Top photo - position 8; bottom photo - position 4.

PROBE: 4B1 COUPON: 13 ALLOY: 304H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 658 C

Bottom : 685 C

Position	1	2	3	4	5	6	7	8
Metal Loss	45	70	80	210	235	50	70	45
Internal Pen.	45	65	75	45	30	55	80	45
Scale	120	135	45	40	40	60	50	30
Deposit	230	90	--	--	--	65	--	--
Bore Scale	25	20	20	25	15	20	15	15

Hardness - Before Exposure: 80 RB

After - Top: 78.0 80.8

Bottom: 79.5 80.0

Coupon Description:

Top: Dark brown, somewhat uneven (as a result of prior spalling) scale/deposit. Some chipping at edges, and spalling at positions.

Bottom; Thin, brown/block deposit, micro-spalled to a grey scale.

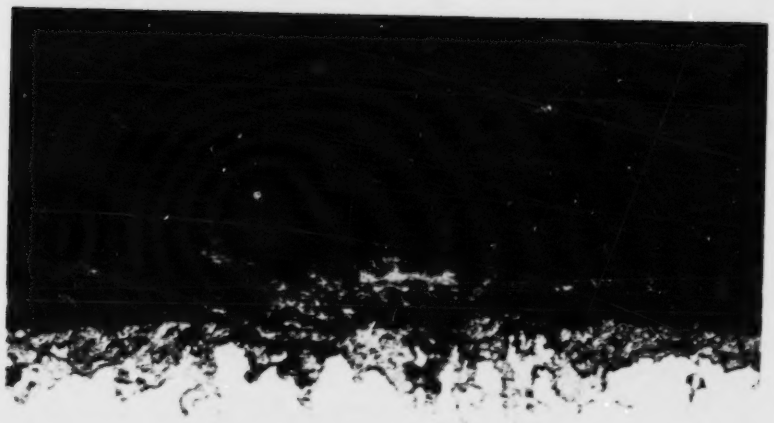
Type of Attack:

Top: Irregular scale/metal interface with many intrusions of scale into the alloy. Some precipitation of grain-boundary globular sulphides.

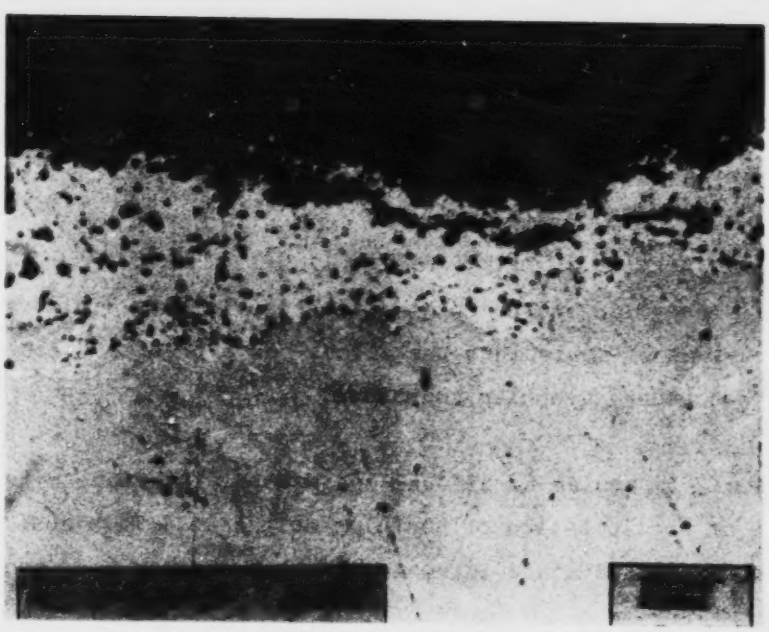
Bottom: Overall a wavy and diffuse scale/metal interface. A well defined zone of precipitation of (probably) globular sulphides. The boundary between this surface zone and the parent austenite is irregular.

Other Comments:

Grain-boundary precipitates through the alloy.



4B1-13-T 3Ø4H 50 um



Photomicrographs of coupon 13 (304H), probe 4B1.
Top photo - position 1-2; bottom photo - position 3.7.

PROBE: 4B1 COUPON: 14 ALLOY: 347H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 662 C

Bottom : 686 C

Position	1	2	3	4	5	6	7	8
Metal Loss	70	215	130	190	155	45	15	20
Internal Pen.	35	60	50	50	30	55	35	40
Scale	110	175	105	25	45	95	--	50
Deposit	180	--	--	--	--	75	--	320
Bore Scale	35	40	35	30	55	30	25	15

Hardness - Before Exposure: 81 RB

After - Top: 82.1 84.1

Bottom: 84.2 83.6

Coupon Description:

Top: Relatively thick, dark brown deposit, spalled to metal at position 6 to 7.

Bottom: Brown/black deposit with micro-spalling to a grey scale, resulting in a somewhat mottled appearing surface.

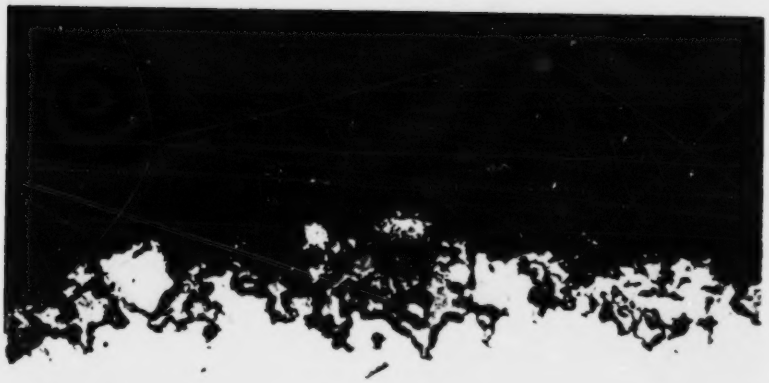
Type of Attack:

Top: Irregular and somewhat diffuse scale/metal interface with many intrusions of scale into the alloy. Some precipitation of grain-boundary globular sulphides.

Bottom: Irregular to diffuse scale/metal interface with a surface zone of precipitation of globular sulphides. This zone seems to occur where the scale intrusions into the alloy are minor.

Other Comments:

Grain-boundary precipitates throughout the alloy.



4B1-14-T 347H | 50 um

4B1-14-B 347H | 50 um

Photomicrographs of coupon 14 (347H), probe 4B1.
Top photo - position 2; bottom photo - position 3-4.

PROBE: 4B1 COUPON: 15 ALLOY: 310

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 666 C

Bottom : 687 C

Position	1	2	3	4	5	6	7	8
Metal Loss	55	60	125	175	125	35	25	25
Internal Pen.	80	125	95	75	50	100	40	40
Scale	25	110	110	100	35	70	25	15
Deposit	1050	470	--	--	--	280	365	300
Bore Scale	TR	10	TR	15	TR	10	TR	TR

Hardness - Before Exposure: 82 RB

After - Top: 88.2 87.2

Bottom: 89.5 88.0

Coupon Description:

Top: Dark brown scale/deposit with some spalling to both a block under layer and to (at positions 2 and 3) the alloy.

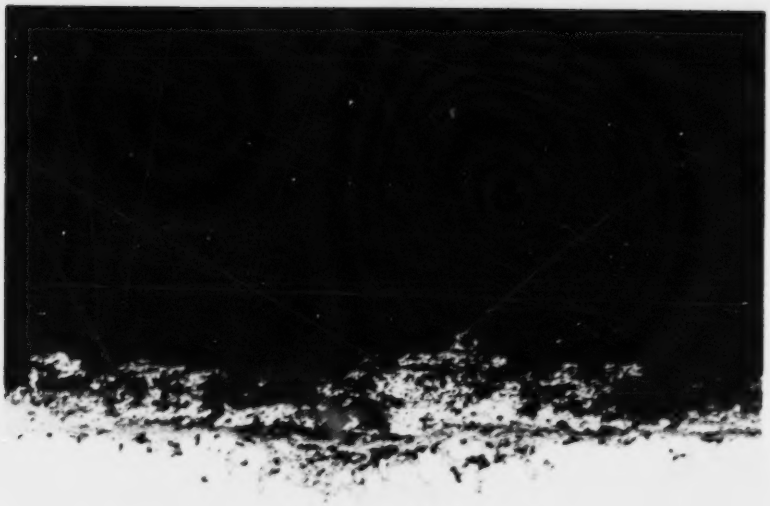
Bottom: Remnants of a thin brown/black deposit over a grey scale. Similar to coupons 14 and 16.

Type of Attack:

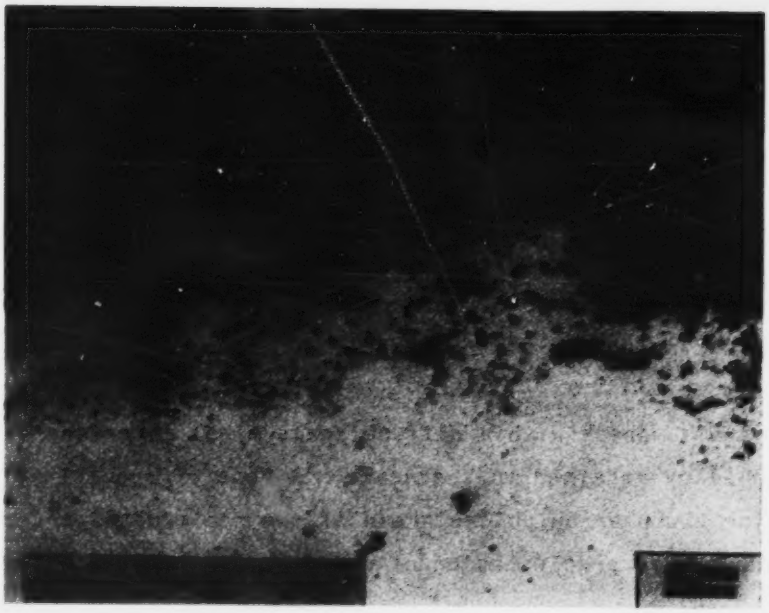
Top: Generally planar scale/metal interface with intrusions of scale into the alloy. A few localized areas of heavier attack.

Bottom: Irregular and, in many areas, a diffuse scale/metal interface. Surface zone of precipitation of globular sulphides.

Other Comments:



4B1-15-T 310 50 um



Photomicrographs of coupon 15 (310), probe 4B1.
Top photo - position 0.6; bottom photo - position 5.2.

PROBE: 4B1 COUPON: 16 ALLOY: 800H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 669 C

Bottom : 689 C

Position	1	2	3	4	5	6	7	8
Metal Loss	10	90	50	110	80	60	5	10
Internal Pen.	80	285	275	175	70	125	110	85
Scale	20	45	20	80	30	20	15	10
Deposit	895	--	700	--	--	580	1350	430
Bore Scale	TR	15	25	TR	15	TR	--	TR

Hardness - Before Exposure: 69 RB

After - Top: 77.6 76.0

Bottom: 78.5 77.9

Coupon Description:

Top: Dark brown deposit; evidence of previous spalling. Spalled to intermediate black or tan layers and to the alloy.

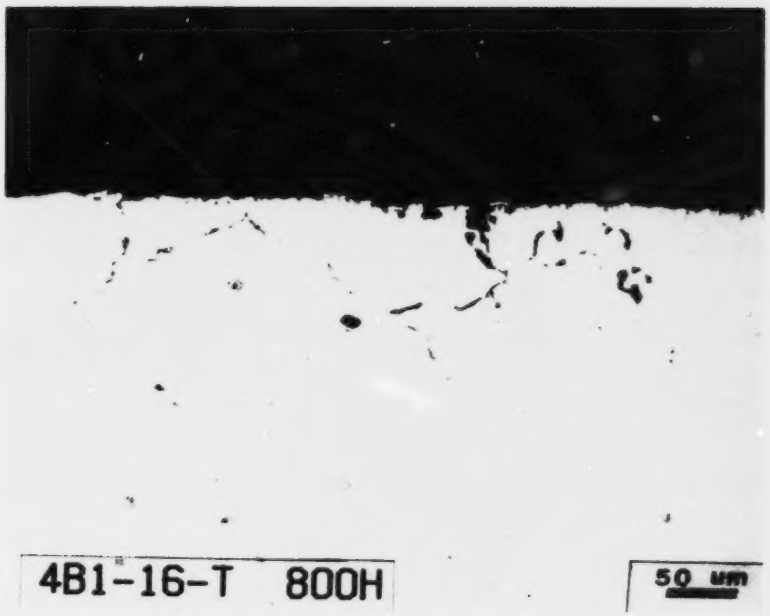
Bottom: Grey scale with small flakes of brown deposit.

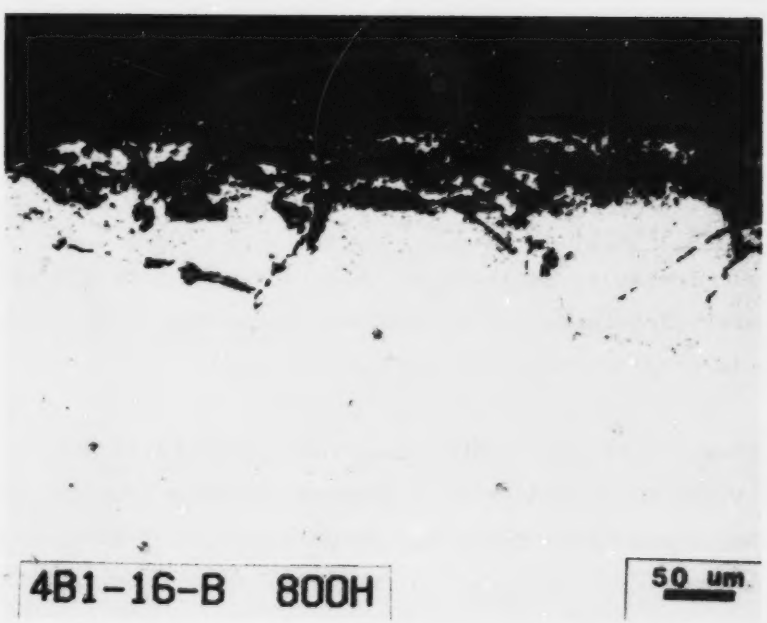
Type of Attack:

Top: Generally very uniform interface with little apparent attack. Intermittent areas of internal penetration, precipitation of oxides/sulphides at the grain boundaries.

Bottom: Areas with a diffuse scale metal interface with particles of alloy retained in the scale. A zone of precipitation of very fine globular sulphides ahead of the scale/metal interface. Other areas have precipitation of oxides/sulphides at the grain boundaries.

Other Comments:





Photomicrographs of coupon 16 (800H), probe 4B1.
Top photo - position 6; bottom photo - position 4

PROBE: 4B1 COUPON: 17 ALLOY: 304H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 673 C

Bottom : 690 C

Position	1	2	3	4	5	6	7	8
Metal Loss	60	100	60	130	150	85	50	40
Internal Pen.	55	75	120	65	30	55	55	50
Scale	100	65	90	60	60	85	70	60
Deposit	240	165	190	--	--	115	175	55
Bore Scale	25	30	TR	25	20	20	15	20

Hardness - Before Exposure: 80 RB

After - Top: 77.0 76.2

Bottom: 79.0 79.4

Coupon Description:

Top: Dark brown deposit, previously spalled. Spalled to alloy at edges.

Bottom: Grey scale with small flakes of brown deposit.

Type of Attack:

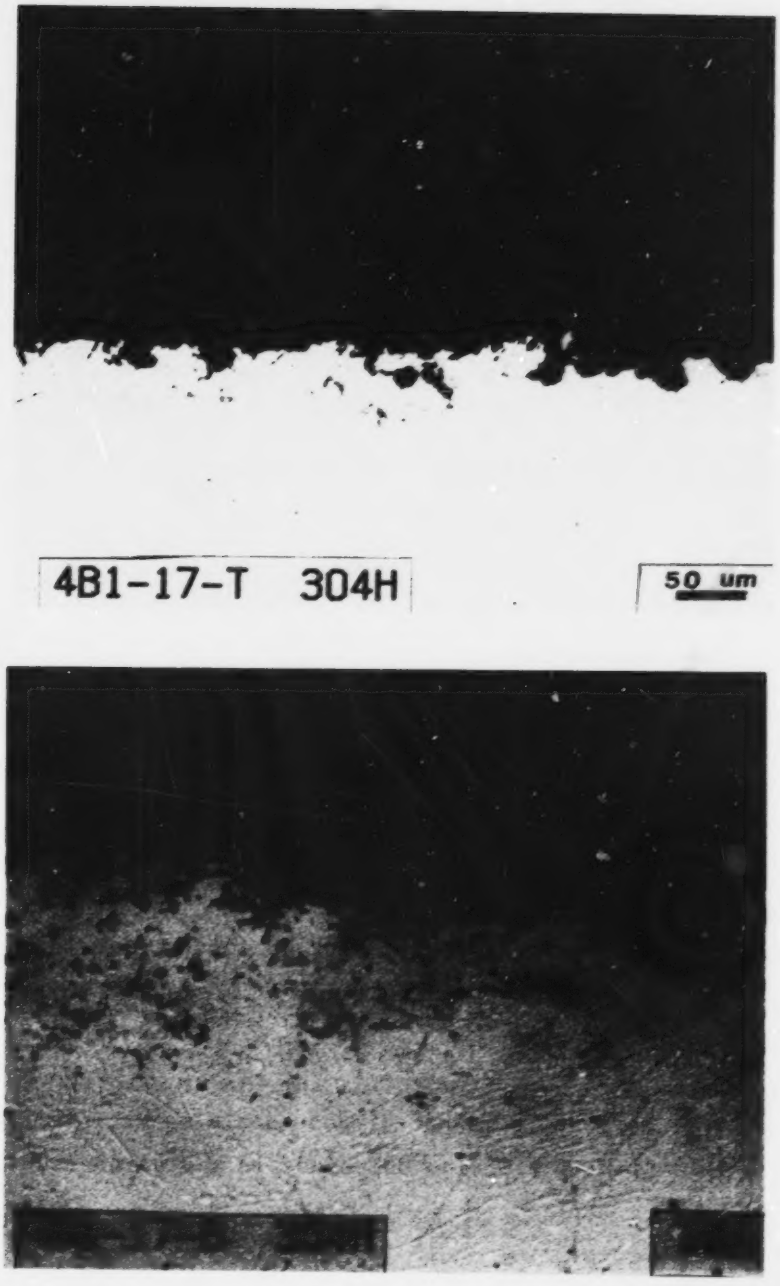
Top: Irregular scale metal interface with some blocky intrusions of scale. Precipitation of globular sulphides. Some areas have a surface zone containing globular sulphides.

Bottom: Wavy scale metal interface, diffuse in areas. Precipitation of globular sulphides in a distinct surface zone in some areas; other areas have precipitation/penetration of scale.

Other Comments:

Sample not etched, but there appears to be precipitates at the grain boundaries throughout the alloy.

Good sample for more intensive metallographic examination.



Photomicrographs of coupon 17 (304H), probe 4B1.
Top photo - position 8; bottom photo - position 3.9.

PROBE: 4B1 COUPON: 18 ALLOY: 310

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 677 C

Bottom : 691 C

Position	1	2	3	4	5	6	7	8
Metal Loss	60	125	160	120	110	80	30	40
Internal Pen.	50	80	45	45	40	70	35	30
Scale	75	105	70	35	45	105	50	55
Deposit	115	265	95	--	--	115	110	70
Bore Scale	30	20	30	40	45	35	25	15

Hardness - Before Exposure: 82 RB

After - Top: 84.5 84.3

Bottom: 82.0 82.3

Coupon Description:

Top: Dark brown deposit, previously spalled. Some spalling to the alloy.

Bottom: Grey scale with some flakes of brown deposit.

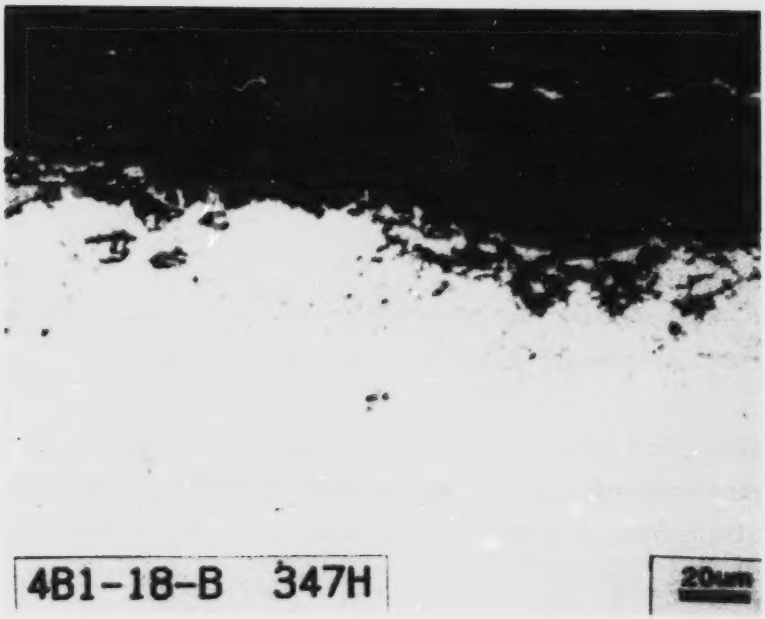
Type of Attack:

Top: Multi-layered deposit, very non-uniform scale/metal interface. Internal precipitation of scale and globular sulphides at grain boundaries.

Bottom: Wavy and somewhat diffuse scale metal interface, precipitation of globular sulphides in a distinct surface zone.

Other Comments:

Precipitates, probably sigma phase, throughout the alloy.



Photomicrographs of coupon 18 (347H), probe 4B1.
Top photo - position 6; bottom photo - position 4.1.

PROBE: 4B1 COUPON: 19 ALLOY: 310

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 681 C

Bottom : 692 C

Position	1	2	3	4	5	6	7	8
Metal Loss	35	40	65	155	150	65	25	45
Internal Pen.	65	75	150	75	15	85	10	30
Scale	20	20	30	65	15	55	10	20
Deposit	340	670	1120	--	--	370	50	400
Bore Scale	--	15	TR	15	10	TR	TR	--

Hardness - Before Exposure: 82 RB

After - Top: 89.9 89.1

Bottom: 91.7 90.0

Coupon Description:

Top: Brown/black deposit of varying thickness. Smooth surface; minor spalling at edge. Some red colour at joint with coupon 20.

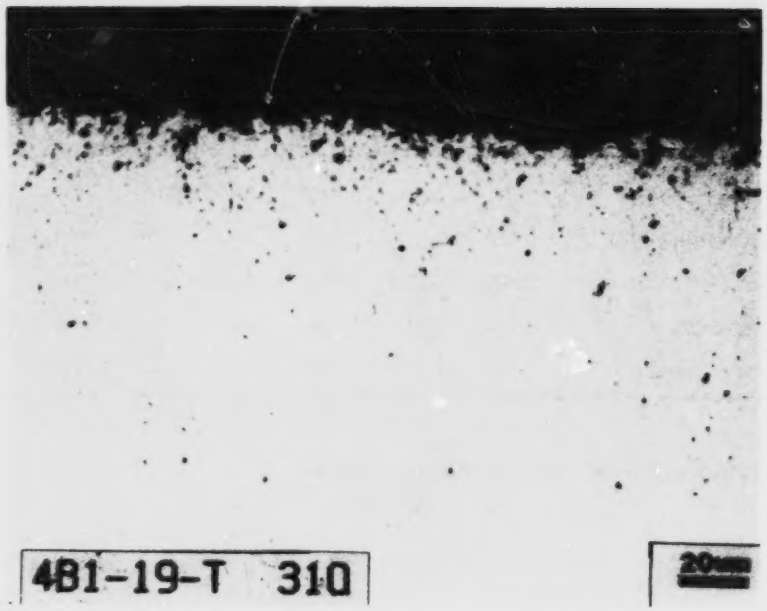
Bottom: Thin, brown deposit with micro-spalling to a grey scale. Much greater coverage of deposit than on coupon 17 and 18.

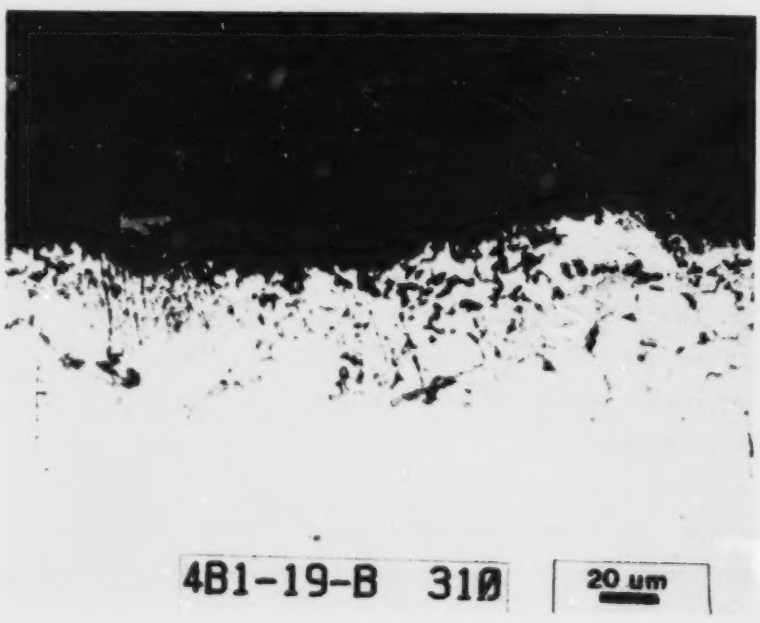
Type of Attack:

Top: Well defined scale/metal interface but with areas of penetration/precipitation of scale into the alloy.

Bottom: Irregular scale/metal interface with scale intrusions and precipitates of scale ahead of the interface in the alloy. Precipitation of globular sulphides in a poorly defined surface zone.

Other Comments:





Photomicrographs of coupon 19 (310), probe 4B1.
Top photo - position 8; bottom photo - position 4.

PROBE: 4B1 COUPON: 20 ALLOY: 800H

EXPOSURE: 8000 h RUNS: 2-3-4-5-6-7-8-9

Estimated average temperature - Top : 685 C

Bottom : 693 C

Position	1	2	3	4	5	6	7	8
Metal Loss	115	120	55	185	140	75	50	85
Internal Pen.	20	50	110	15	TR	50	25	10
Scale	20	15	50	20	15	25	20	45
Deposit	--	80	30	--	--	85	--	--
Bore Scale	--	TR	TR	--	--	TR	TR	--

Hardness - Before Exposure: 69 RB

After - Top: 78.1 76.0

Bottom: 80.1 77.8

Coupon Description:

Top: Thin black deposit, thickens at sides. Some spalling to the alloy. Red colour at 19/20 joint.

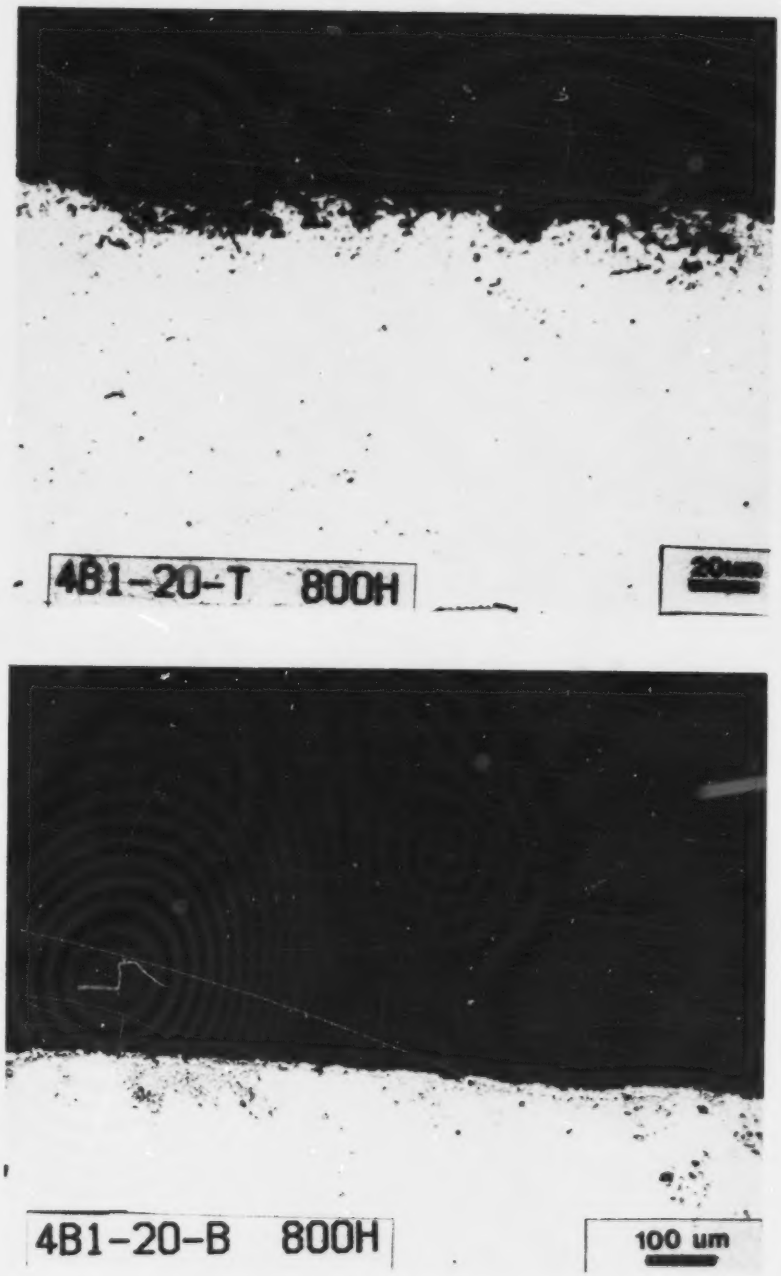
Bottom: Thin brown/black deposit with a small amount of micro-spalling.

Type of Attack:

Top: Well defined scale/metal interface in some areas, poorly defined and diffuse in others with particles of alloy retained in the scale. Areas of more extensive internal precipitation of oxides and sulphides

Bottom: Wavy and diffuse to well defined scale/metal interface. Some areas have a zone of precipitation of globular sulphides in a surface zone.

Other Comments:



Photomicrographs of coupon 20 (800H), probe 4B1.
Top photo - position 7.5; bottom photo - position 2.5.

PMRL 86-39 (TR)

APPENDIX 3

DATA SHEETS AND PHOTOMICROGRAPHS

OF

PROBE 9DL3

4000-h EXPOSURE

RUNS 6, 7, 8 AND 9

PROBE: 9DL3 COUPON: 1 ALLOY: 800H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	20	3815	3865	2945	4185	90	20	25
Internal Pen.	230	1180	720	795	625	200	175	160
Scale	TR	--	--	--	--	80	TR	15
Deposit	15	--	--	--	--	--	--	15
Bore Scale	15	--	--	--	--	TR	10	15

Hardness - Before Exposure: 69 RB

After - Top: 71.0 69.4

Bottom:

Coupon Description:

Top: Flow pattern of the bed is obvious on the coupon with a darker strip about 1 cm wide at the top centre; the rest of the top has a dull brown matted appearance.

Bottom: Massive attack with over 2 mm metal loss, threaded region gone. Corrosion extends to just over half way up the coupon. Surface of the corroded region is covered with a black scale.

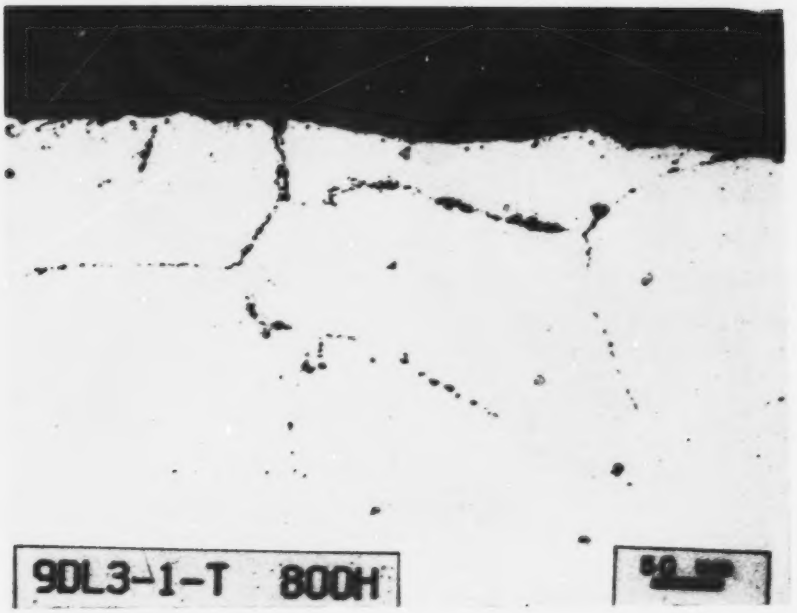
Type of Attack:

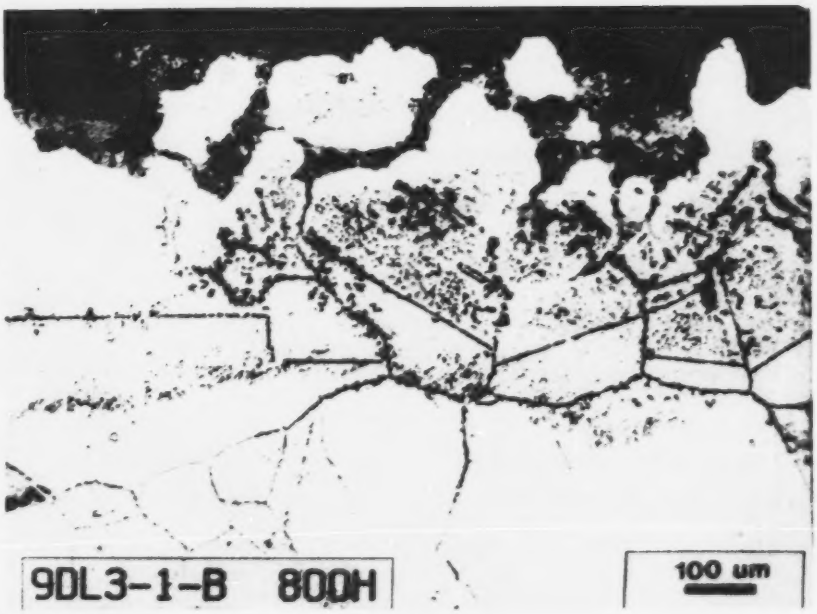
Top: Relatively little attack; precipitation of oxides/sulphides at grain boundaries with grain-boundary globular sulphides at greatest depth.

Bottom: Massive catastrophic attack; contains some structures that appear to be the result of solidification.

Other Comments:

Junction between the region of massive attack and minor attack is very clearly defined.





Photomicrographs of coupon 1 (800H), probe 9DL3.
Top photo - position 0.1; bottom photo - position 4.2.

PROBE: 9DL3 COUPON: 2 ALLOY: 347H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	25	135	115	120	95	100	15	25
Internal Pen.	45	110	95	105	100	70	40	30
Scale	10	70	45	130	70	40	10	TR
Deposit	--	--	--	--	--	--	--	--
Bore Scale	115	110	100	110	120	--	115	95

Hardness - Before Exposure: 81 RB

After - Top: 81.0 79.0

Bottom: 77.1 78.5

Coupon Description:

Top: Flow pattern is obvious with a darker strip about 1 cm wide at top centre; the rest of the top has a brown mottled appearance.

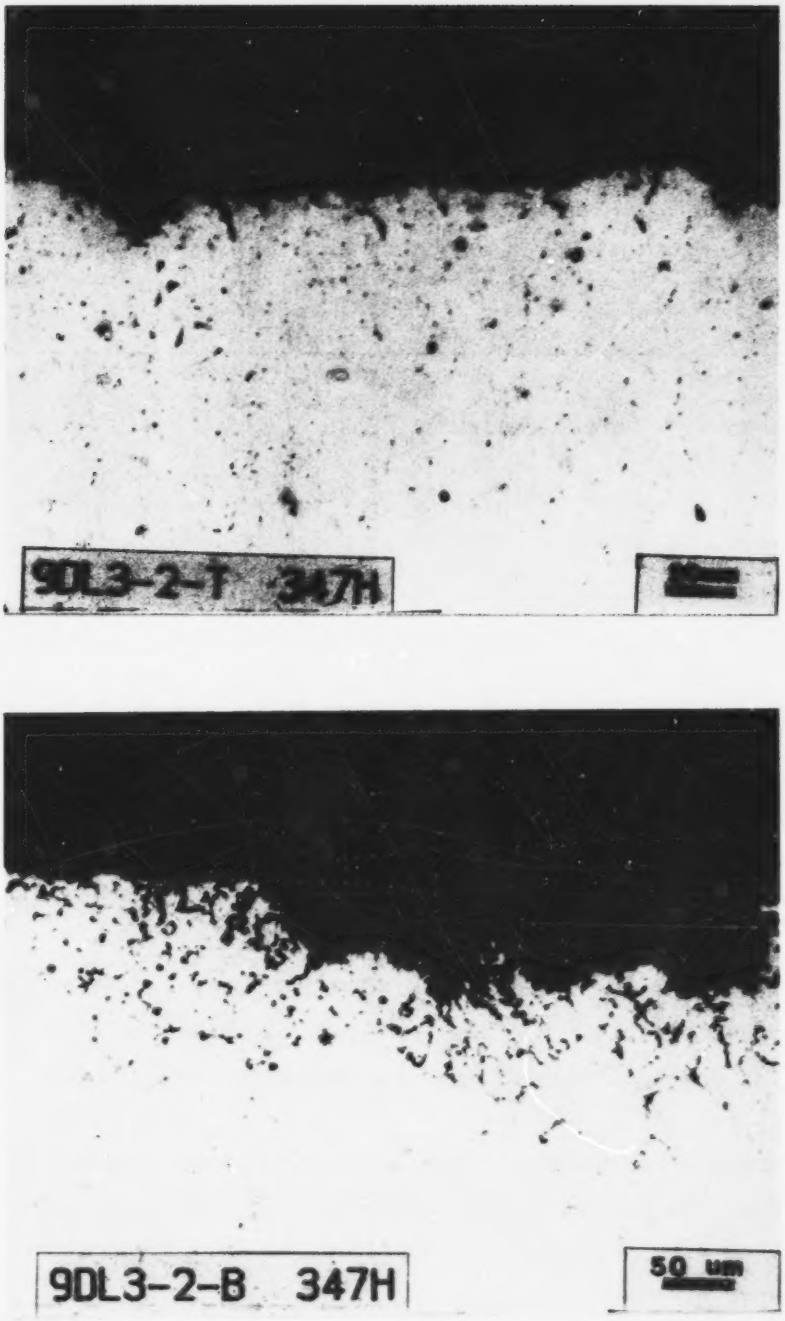
Bottom: Areas of heavy corrosion adjacent to coupon 1. The remainder of the bottom has a black, somewhat rough-surfaced scale/deposit.

Type of Attack:

Top: Very little obvious attack; somewhat irregular scale/metal interface; minor precipitation of globular sulphides.

Bottom: Local regions of attack that may be related to the massive attack of the 800H coupon 1. Precipitation of oxides and sulphides beneath an irregular scale/metal interface.

Other Comments:



Photomicrographs of coupon 2 (347H), probe 9DL3.
Top photo - position 7.8; bottom photo - position 4.

PROBE: 9DL3 COUPON: 3 ALLOY: 310

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	5	10	25	45	25	35	20	-10
Internal Pen.	55	65	110	100	70	80	55	35
Scale	10	20	45	25	35	15	TR	TR
Deposit	--	--	--	--	--	--	--	--
Bore Scale	--	--	--	--	--	--	TR	TR

Hardness - Before Exposure: 82 RB

After - Top: 84.2 84.6

Bottom: 82.4 82.9

Coupon Description:

Top: Flow pattern more pronounced than on coupons 1 and 2 with a brown/black strip at top centre. The remainder of the top has a brown, rusty-appearing dull scale/deposit.

Bottom: Brown/black dull surface with small (1 mm) flakes of brown deposit.

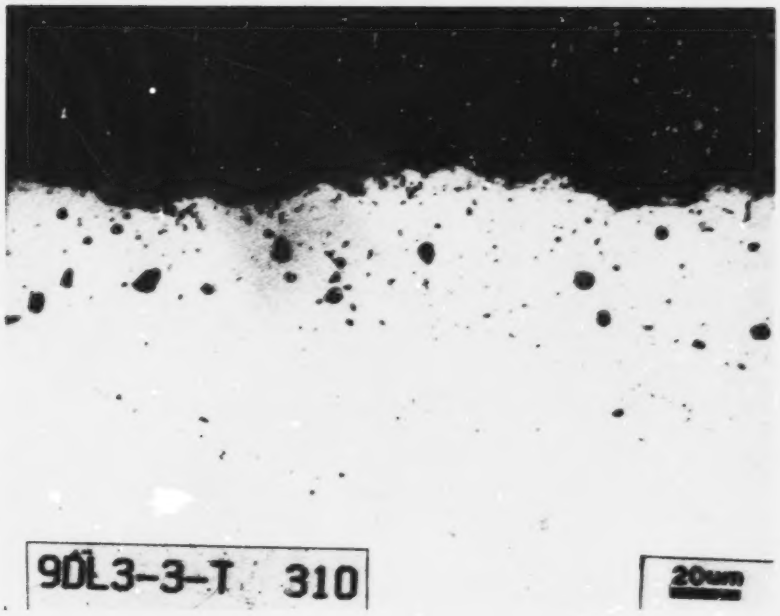
Type of Attack:

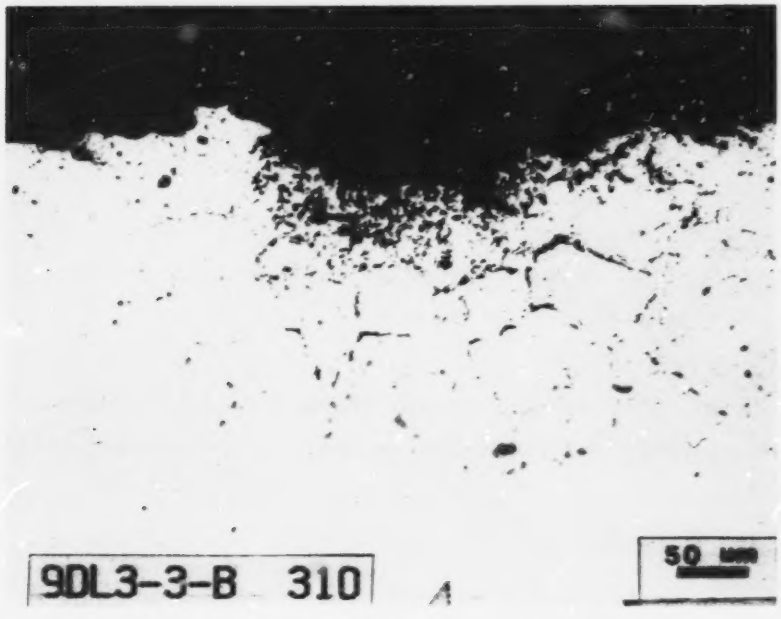
Top: Little attack; irregular scale/metal interface; precipitation of relatively large (8μm) globular sulphides in a surface zone. Also precipitation of much smaller globular sulphides.

Bottom: Non-uniform attack with a few local regions having more extensive penetration/precipitation of oxides/sulphides. Relatively large globular sulphides appear to be associated with these areas of heavy attack.

Other Comments:

Precipitation of sigma and carbides throughout the alloy. These appear to decrease close to the surface in the zone of precipitation of globular sulphides.





Photomicrographs of coupon 3 (310), probe 9DL3.
Top photo - position 7; bottom photo - position 4.5.

PROBE: 9DL3 COUPON: 4 ALLOY: HK40

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	20	160	35	30	175	85	40	-10
Internal Pen.	165	220	190	205	230	250	175	130
Scale	10	95	20	35	115	50	10	TR
Deposit	--	--	--	50	--	--	50	--
Bore Scale	--	--	--	--	--	--	--	--

Hardness - Before Exposure: 85 RB

After - Top: 93.0 93.8

Bottom: 94.1 94.3

Coupon Description:

Top: Dark flow pattern with a strip about 1.5 cm wide. Sides are dull brown.

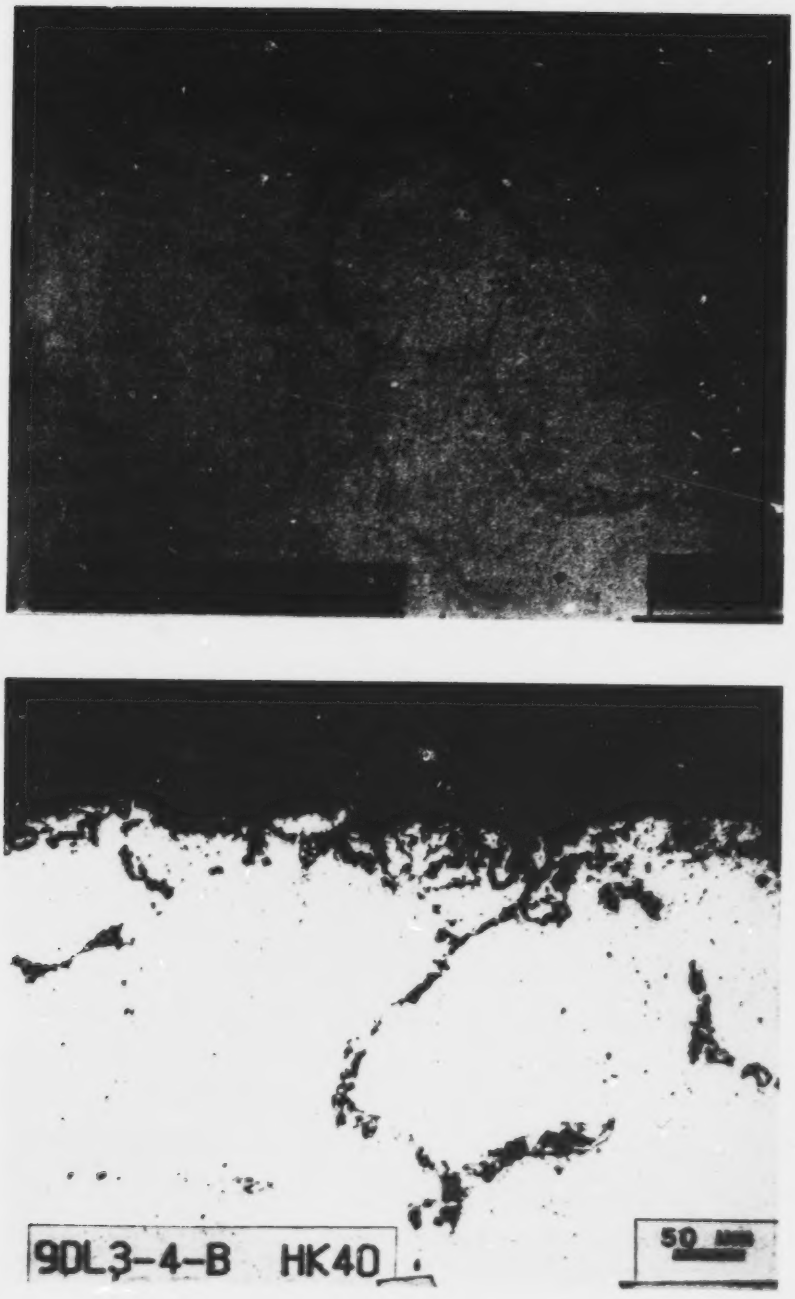
Bottom: Somewhat mottled appearing brown deposit with flakes of tan deposits on the sides. These tan deposits more pronounced on the east side.

Type of Attack:

Top: Little attack of the surface; precipitation of oxides/sulphides in the interdendritic phase.

Bottom: Diffuse scale/metal interface in local areas; extensive precipitation of oxides/sulphides in the interdendritic phase.

Other Comments:



Photomicrographs of coupon 4 (HK40), probe 9DL3.
Top photo - position 8; bottom photo - position 4.9.

PROBE: 9DL3 COUPON: 5 ALLOY: 253MA

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	5	70	70	75	20	100	35	45
Internal Pen.	80	85	85	55	45	85	95	75
Scale	--	15	70	100	20	15	10	20
Deposit	25	--	--	--	--	--	--	--
Bore Scale	--	--	--	--	--	TR	20	30

Hardness - Before Exposure: 89 RB

After - Top: 85.6 85.7

Bottom: 85.8 85.8

Coupon Description:

Top: Dark flow pattern strip about 2 cm wide with the start of a light tan strip on the centre. Sides are a smooth, dull, brown deposit.

Bottom: Brown/tan/black mottled appearing deposit. Some brown flakes of deposit on the surface.

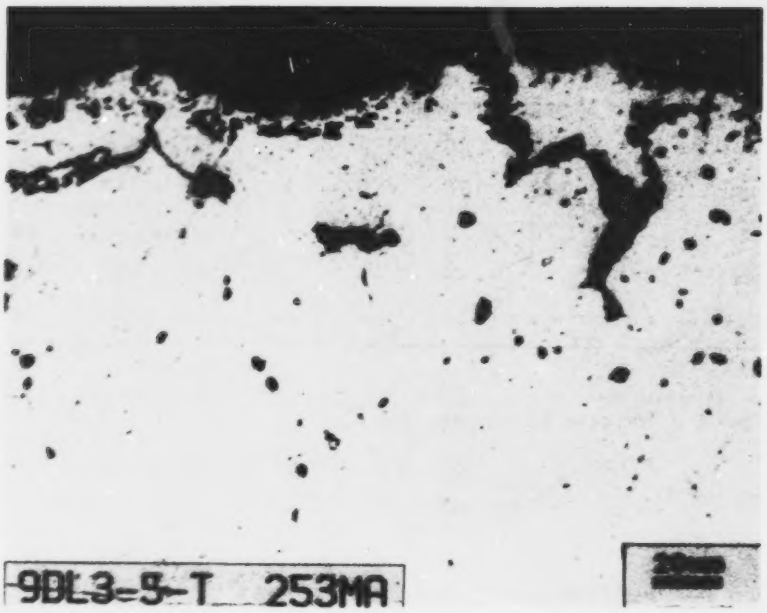
Type of Attack:

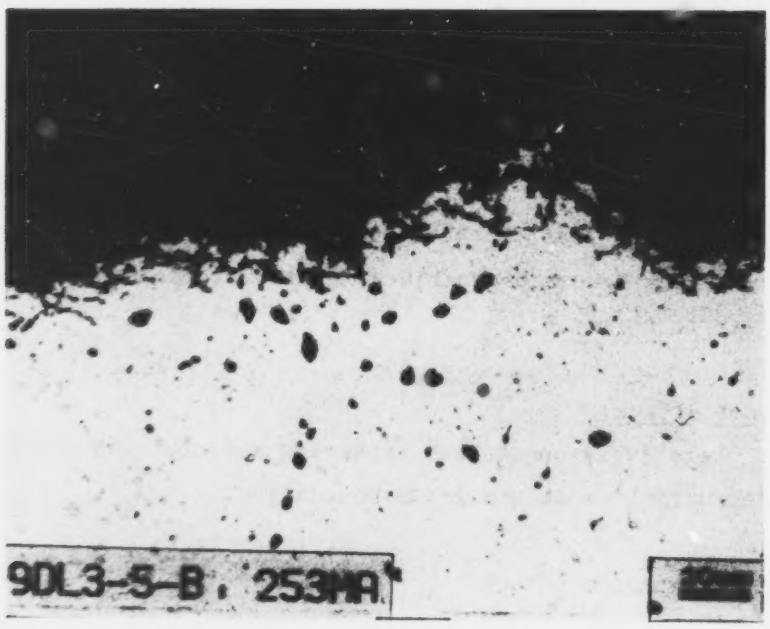
Top: Wavy scale/metal interface; intrusions of scale; precipitation of grain-boundary globular sulphides - some relatively large.

Bottom: Very irregular scale/metal interface - wavy on a 100 μm scale with penetration/precipitation of oxide/sulphides. Precipitation of grain-boundary globular sulphides at the greatest depth.

Other Comments:

Precipitates throughout the alloy but fewer at or towards the surface in the zone of precipitation of globular sulphides. Crystallographically oriented precipitates appear to be more numerous directly below zones of heavy attack. This may be an artifact from polishing.





Photomicrographs of coupon 5 (253MA), probe 9DL3.
Top photo - position 0.1; bottom photo - position 4.3.

PROBE: 9DL3 COUPON: 6 ALLOY: 800H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	--	20	2490	1850	1995	15	5	10
Internal Pen.	185	170	475	490	525	120	135	190
Scale	20	20	2345	1690	1600	15	TR	10
Deposit	--	--	--	--	--	80	--	--
Bore Scale	--	10	--	--	--	--	TR	10

Hardness - Before Exposure: 69 RB

After - Top: 66.6 69.0

Bottom: 66.0 67.4

Coupon Description:

Top: Dark flow pattern strip about 2.5 cm wide with a light tan centre strip. Remainder is a dull brown deposit. Some bulging at the 6/7 joint with what appears to be corrosion products on the surface.

Bottom: Extensive corrosion, especially towards coupon 7 but no obvious perforation. Attack extends nearly half way up on the west side, somewhat less on the east side. Areas of bottom not showing heavy attack have a brown/black mottled appearing scale/ deposit similar to coupon 5.

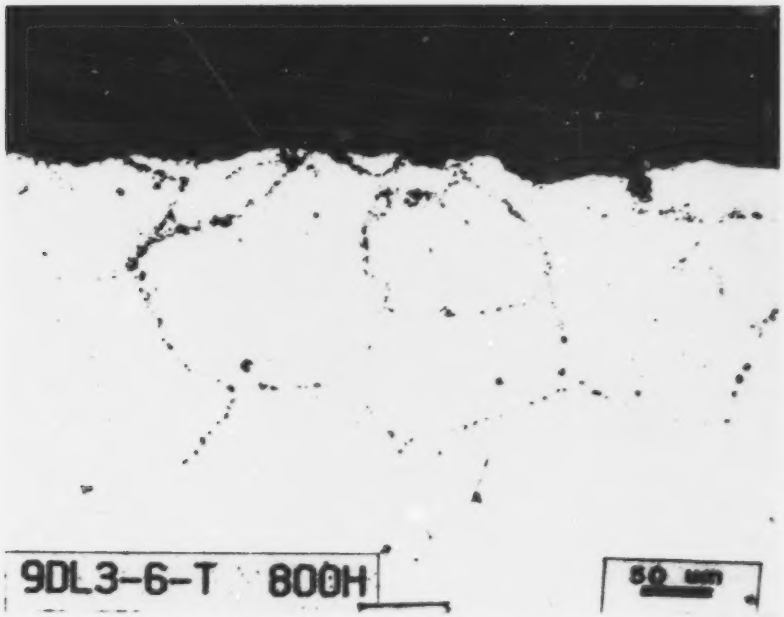
Type of Attack:

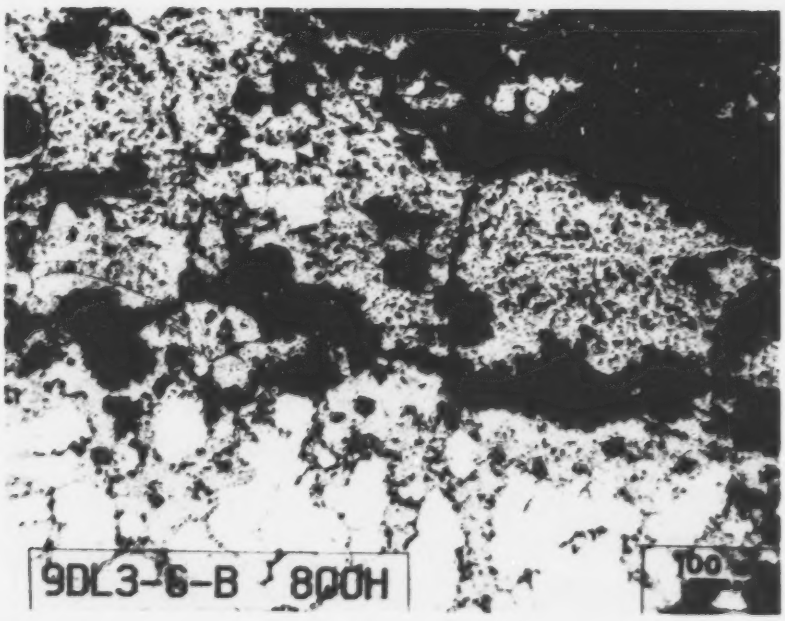
Top: Relatively unattacked appearing surface with precipitation of oxides/sulphides at the grain boundaries.

Bottom: Massive attack.

Other Comments:

Grain boundary and other precipitates throughout alloy.





Photomicrographs of coupon 6 (800H), probe 9DL3.
Top photo - position 7.4; bottom photo - position 5.1.

PROBE: 9DL3 COUPON: 7 ALLOY: 347H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	5	35	70	105	80	20	10	--
Internal Pen.	30	35	90	115	75	45	25	25
Scale	25	20	50	60	50	35	--	--
Deposit	--	--	--	--	--	--	--	--
Bore Scale	75	105	120	65	120	20	65	50

Hardness - Before Exposure: 81 RB

After - Top: 67.0 65.1

Bottom: 77.1 79.8

Coupon Description:

Top: Similar to coupon 6; flow pattern on top; sides are dull brown; corrosion products at 6/7 joint.

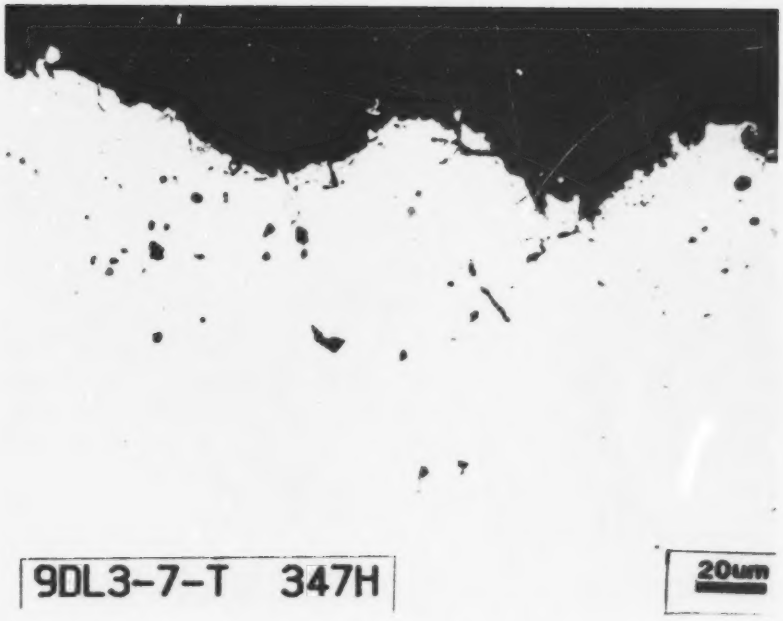
Bottom: Dull black scale; areas of heavy attack adjacent to coupon 6; some tan deposits adjacent to coupon 8.

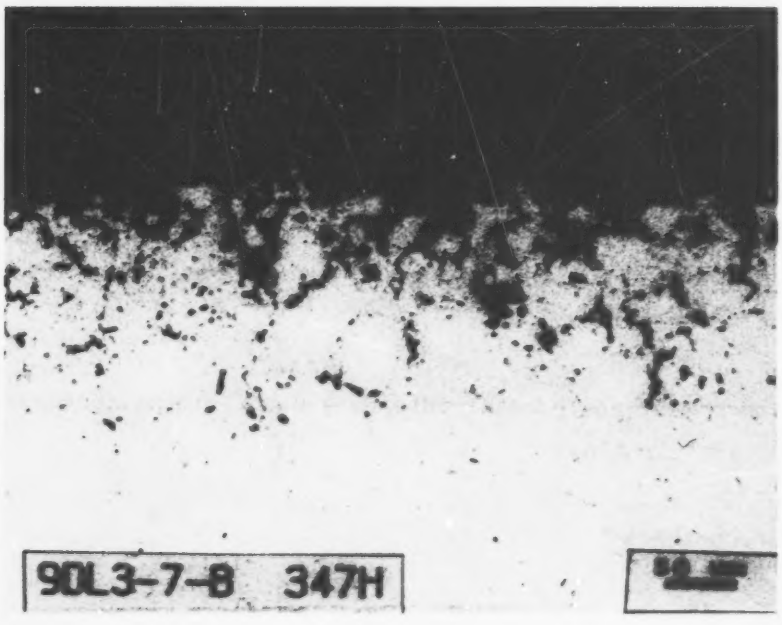
Type of Attack:

Top: Little obvious attack; wavy scale/metal interface; minor intrusion of scale; precipitation of globular sulphides.

Bottom: Irregular scale/metal interface, regions of heavier attack; precipitation of oxides/sulphides especially at the grain boundaries; precipitation of grain-boundary globular sulphides at greater depth.

Other Comments:





Photomicrographs of coupon 7 (347H), probe 9DL3.
Top photo - position 0.4;bottom photo - position 4.4.

PROBE: 9DL3 COUPON: 8 ALLOY: 310

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	10	20	25	35	45	15	20	10
Internal Pen.	50	95	55	50	50	40	45	40
Scale	15	15	20	40	35	15	TR	TR
Deposit	--	--	--	--	35	--	--	--
Bore Scale	10	15	TR	TR	10	10	15	10

Hardness - Before Exposure: 82 RB

After - Top: 80.1 83.0

Bottom: 81.9 82.8

Coupon Description:

Top: Flow pattern reaches its maximum width; black at top centre; appears to be corrosion at the 8/9 joint with some bulging at these areas. Sides have a dark brown deposit.

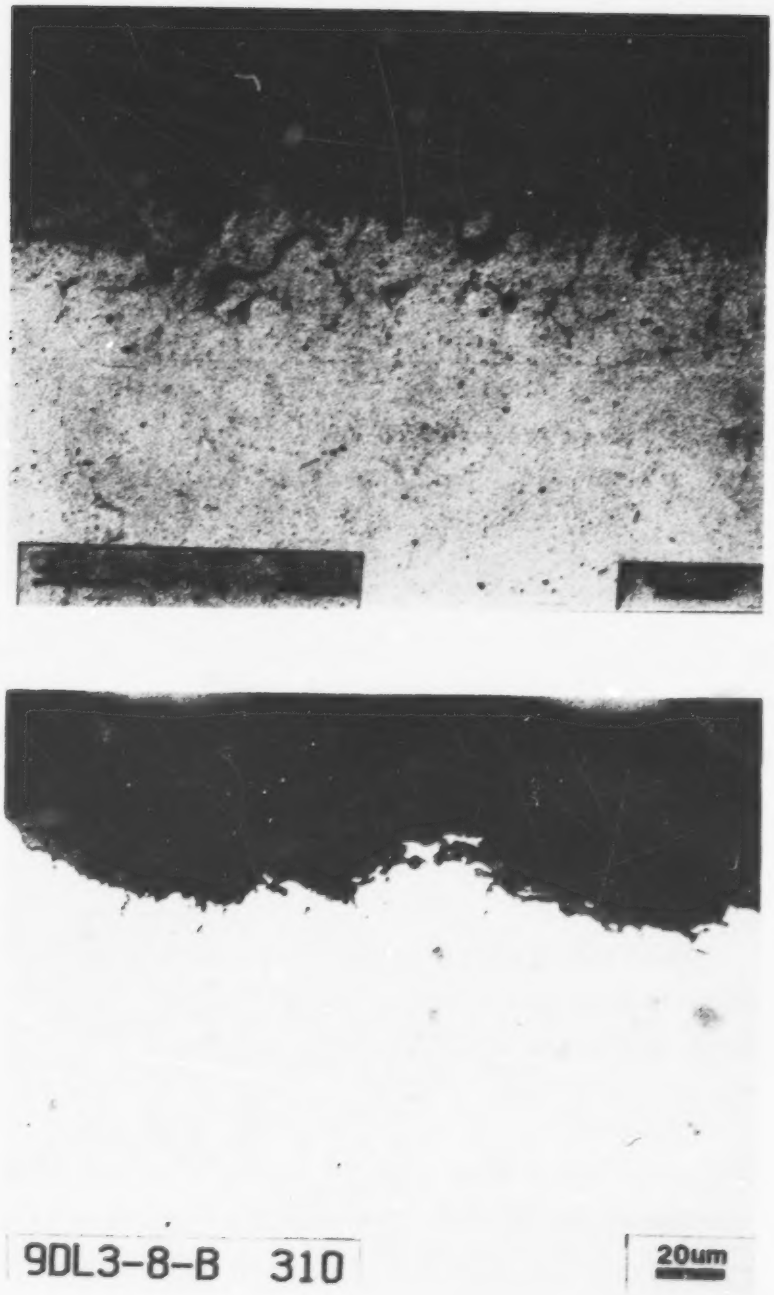
Bottom: Mottled black/brown/tan deposi; appears to be very thin.

Type of Attack:

Top: Little obvious attack; smooth scale/metal interface with penetration of scale at the grain boundaries; some precipitation of globular sulphides.

Bottom: Wavy scale/metal interface with internal precipitation of globular sulphides.

Other Comments:



Photomicrographs of coupon 8 (310), probe 9DL3.
Top photo - position 7.5; bottom photo - position 3.6.

PROBE: 9DL3 COUPON: 9 ALLOY: HK40

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	60	35	35	30	25	55	35	--
Internal Pen.	180	185	110	60	50	210	205	100
Scale	45	40	20	20	25	30	30	TR
Deposit	--	--	--	--	--	--	--	--
Bore Scale	--	--	--	--	--	--	--	--

Hardness - Before Exposure: 85 RB

After - Top: 87.0 91.9

Bottom: 88.1 87.8

Coupon Description:

Top: Flow pattern is less distinct; top centre is mottled black/brown/tan. West side is a dull brown to tan colour, east side is a dull black.

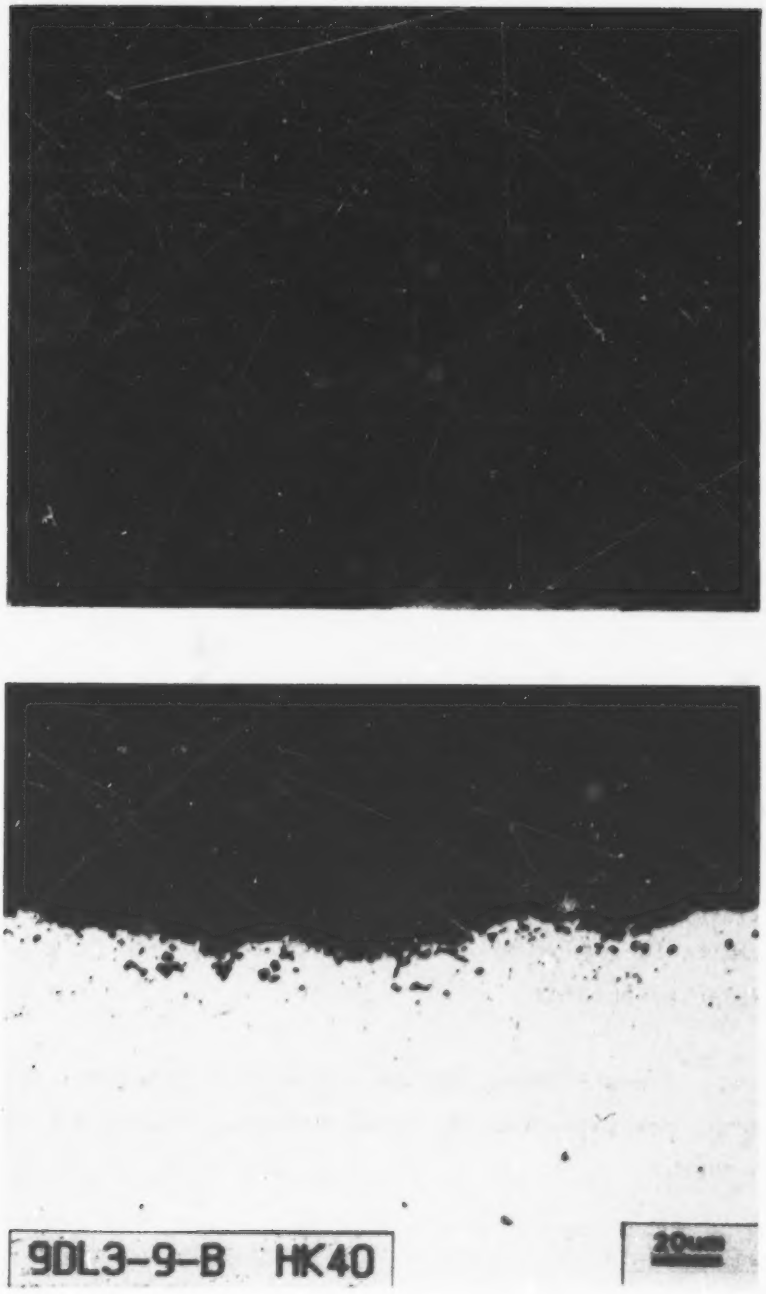
Bottom: Mottled black/brown/tan, dull, thin scale/deposit.

Type of Attack:

Top: Little obvious attack; general precipitation of oxides/sulphides in a narrow (10-20μm) zone at the surface. More extensive precipitation of oxides/sulphides in the interdendritic phase.

Bottom: Wavy scale/metal interface; little attack of the interdendritic phase; some precipitation of globular sulphides.

Other Comments:



Photomicrographs of coupon 9 (HK40), probe 9DL3.
Top photo - position 0.8; bottom photo - position 3.5.

PROBE: 9DL3 COUPON: 10 ALLOY: 253MA

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	55	60	70	20	105	95	150	130
Internal Pen.	130	160	150	65	120	145	140	150
Scale	50	30	20	20	45	55	50	35
Deposit	--	--	--	--	--	--	--	--
Bore Scale	35	30	--	20	TR	30	30	20

Hardness - Before Exposure: 89 RB

After - Top: 85.7 85.4

Bottom: 85.0 84.7

Coupon Description:

Top: Some flow pattern visible; black- brown flakes of scale/ deposit on top.

Bottom: Dull grey/black scale/deposit.

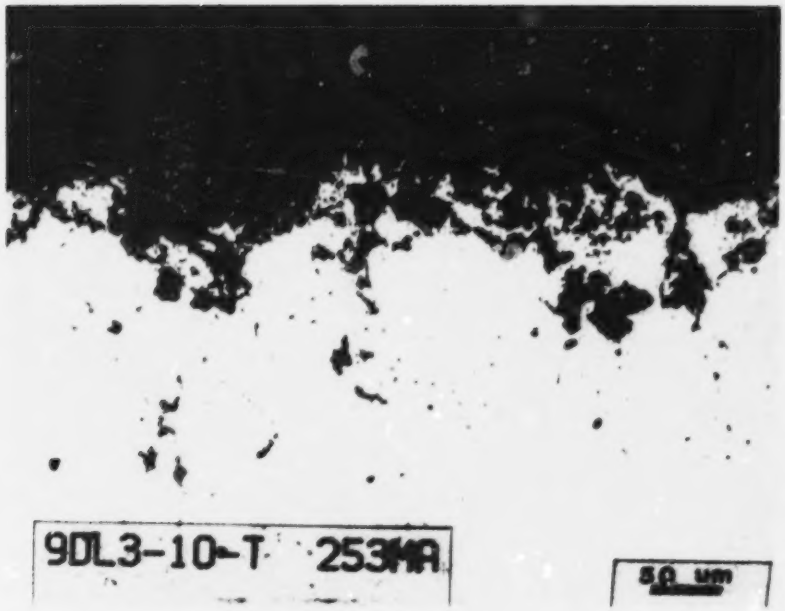
Type of Attack:

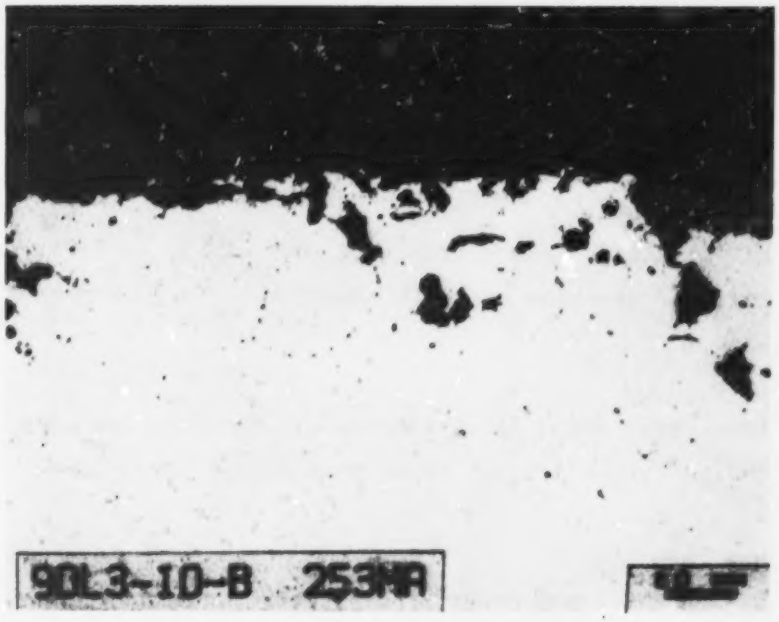
Top: Very irregular scale/metal interface;, extensive internal precipitation of oxides/sulphides; precipitation of grain-boundary globular sulphides.

Bottom: Somewhat more uniform scale/metal interface than at the top; internal precipitation of oxides and grain-boundary globular sulphides.

Other Comments:

Precipitation throughout the alloy - both inter- and intra-granular; precipitates appear fewer in the zone near the surface where corrosion-related precipitates occur.





Photomicrographs of coupon 10 (253MA), probe 9DL3.
Top photo - position 7.9; bottom photo - position 3.4.

PROBE: 9DL3 COUPON: 11 ALLOY: 800H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	85	5	40	50	120	40	110	10
Internal Pen.	385	290	280	135	365	310	360	265
Scale	90	25	30	20	45	45	45	15
Deposit	--	--	--	--	--	--	--	--
Bore Scale	25	TR	15	10	10	TR	TR	TR

Hardness - Before Exposure: 69 RB

After - Top: 68.5 70.0

Bottom: 65.4 67.0

Coupon Description:

Top: Brown/white mottled scale/deposit. East side - black/brown deposit; west side - brown deposit. A few remnants of a thicker, dull brown deposit at the 11/12 joint.

Bottom: Uniform, dull, smooth, grey/black scale deposit.

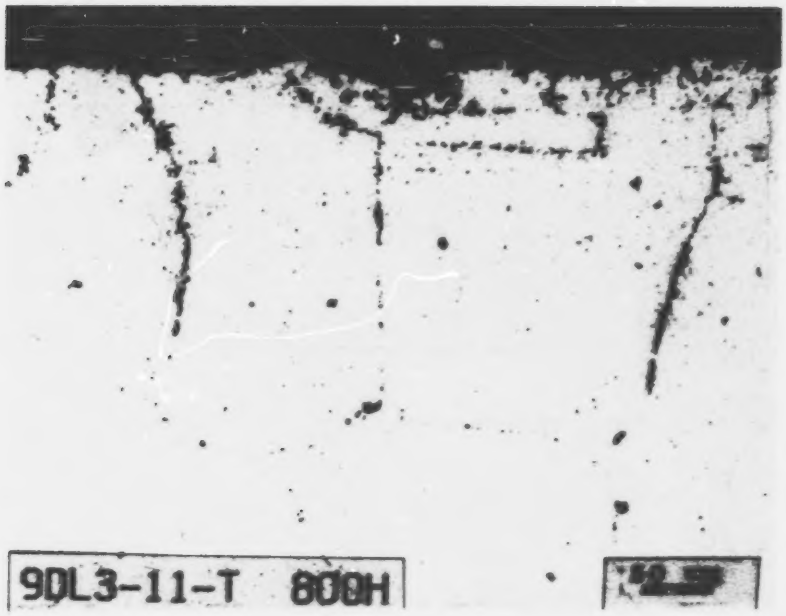
Type of Attack:

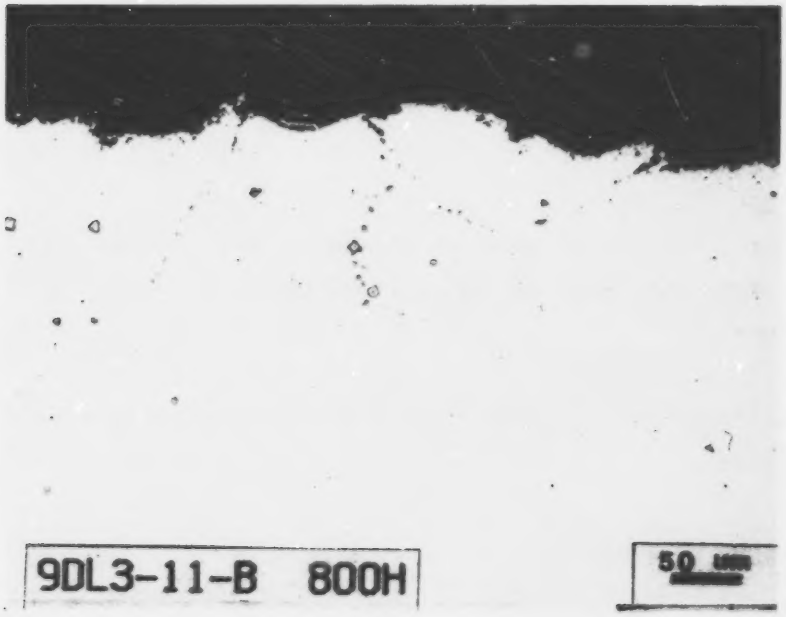
Top: Little obvious attack over much of the surface; precipitation of oxides/sulphides at grain boundaries; a few areas of heavier attack.

Bottom: Wavy scale metal interface; precipitation of grain-boundary globular sulphides, but fewer than at the top.

Other Comments:

Grain-boundary and other precipitates throughout alloy.





Photomicrographs of coupon 11 (800H), probe 9DL3.
Top photo - position 8.0; bottom photo - position 4.9.

PROBE: 9DL3 COUPON: 12 ALLOY: 347H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	5	5	15	30	35	50	10	20
Internal Pen.	25	30	35	35	30	30	25	30
Scale	20	TR	40	40	40	20	25	TR
Deposit	--	--	--	--	--	--	--	--
Bore Scale	40	110	80	TR	--	--	--	--

Hardness - Before Exposure: 81 RB

After - Top: 74.8 74.9

Bottom: 78.4 78.9

Coupon Description:

Top: Tan/brown scale deposit; sides dull black. Some bulging of the threaded portion of the coupon at the 12/13 joint.

Bottom: Dull, grey/black, smooth scale/deposit.

Type of Attack:

Top: Wavy scale/metal interface in some regions; little obvious attack over much of the surface giving a somewhat "pitted" appearing surface.

Bottom: Similar to the top but with more uniform, although minor, attack.

Other Comments:

Photomicrographs of coupon 12 (347H), probe 9DL3.
Top photo - position 7.6; bottom photo - position 3.6.

PROBE: 9DL3 COUPON: 13 ALLOY: 310

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	15	5	--	25	35	65	70	10
Internal Pen.	45	135	45	40	160	175	180	45
Scale	15	TR	25	20	30	30	30	10
Deposit	--	--	--	--	--	--	--	--
Bore Scale	TR	--	--	TR	10	10	10	TR

Hardness - Before Exposure: 82 RB

After - Top: 80.1 83.0

Bottom: 82.1 82.0

Coupon Description:

Top: Dull, brown/black scale deposit. Sides somewhat darker colour.

Bottom: Uniform, dull, smooth, grey/black scale/deposit.

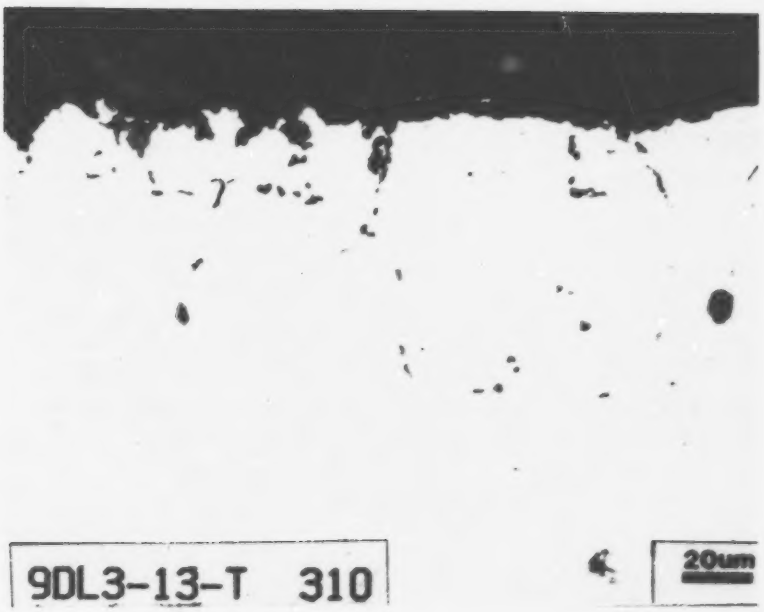
Type of Attack:

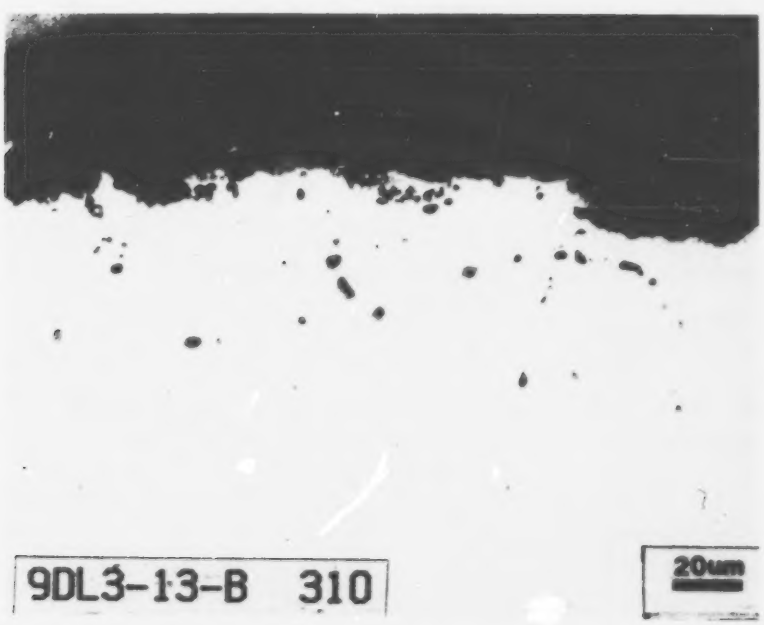
Top: Little obvious attack; minor precipitation of oxide at the grain boundaries; precipitation of grain-boundary globular sulphides at greater depth. Internal attack is heavier toward the sides of the coupon.

Bottom: Somewhat more attack than at the top, but less than at the sides where there is grain-boundary precipitation of oxides and sulphides.

Other Comments:

Precipitation of sigma and carbides throughout the alloy. Precipitates are fewer in the surface zone where corrosion related precipitation occurs.





Photomicrographs of coupon 13 (310), probe 9DL3.
Top photo - position 0.5; bottom photo - position 4.0.

PROBE: 9DL3 COUPON: 14 ALLOY: HK40

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	15	--	40	30	15	45	55	100
Internal Pen.	90	165	255	170	230	250	205	215
Scale	20	15	40	20	30	35	30	40
Deposit	--	--	--	--	--	--	--	--
Bore Scale	TR	--	--	--	--	--	--	TR

Hardness - Before Exposure: 85 RB

After - Top: 92.9 90.4

Bottom: 91.0 91.5

Coupon Description:

Top: Thin dull black scale with a large "white" area (perhaps alloy surface) with black flecks.

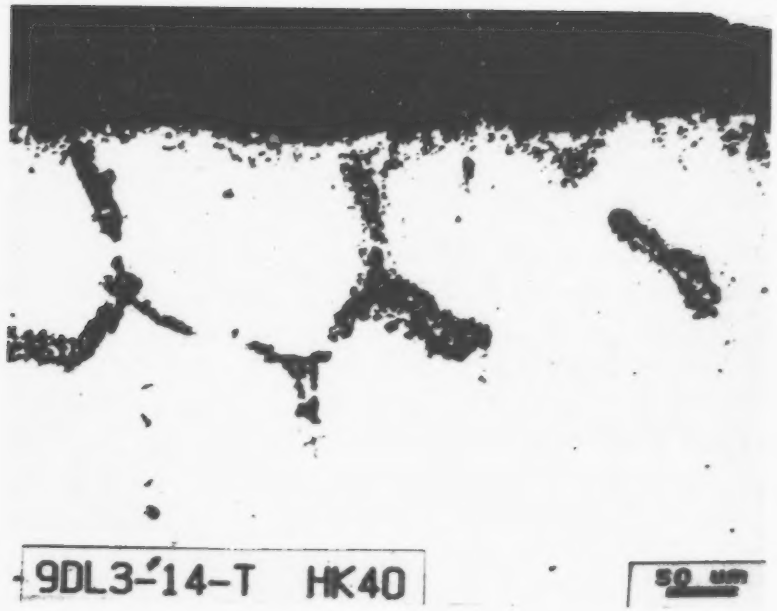
Bottom: Dull, somewhat rough, grey/black scale/deposit.

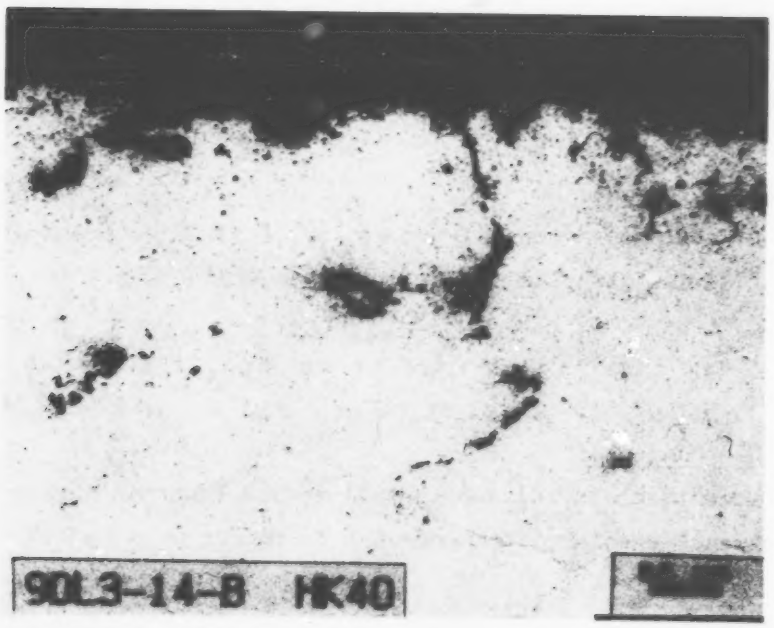
Type of Attack:

Top: Uniform 20 μm thick zone of internal precipitation along the surface; precipitation of oxides/sulphides in the interdendritic phase.

Bottom: Similar to the top but with a more irregular scale/metal interface and less internal attack of the interdendritic phase.

Other Comments:





Photomicrographs of coupon 14 (HK40), probe 9DL3.
Top photo - position 8.0; bottom photo - position 3.1.

PROBE: 9DL3 COUPON: 15 ALLOY: 253MA

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	105	95	160	155	115	130	130	60
Internal Pen.	165	145	175	165	180	180	170	145
Scale	50	45	80	60	55	75	70	110
Deposit	--	--	--	--	--	--	--	--
Bore Scale	--	--	--	--	--	--	--	--

Hardness - Before Exposure: 89 RB

After - Top: 86.9 87.0

Bottom: 84.2 83.8

Coupon Description:

Top: Most of the surface has a dull black scale. Some patches of a brown deposit.

Bottom: Dull, grey/black, somewhat rough, scale.

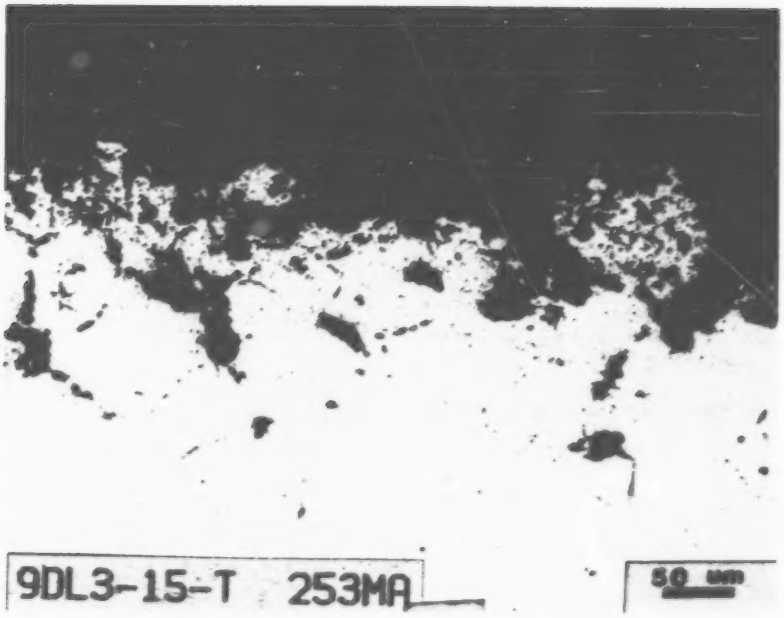
Type of Attack:

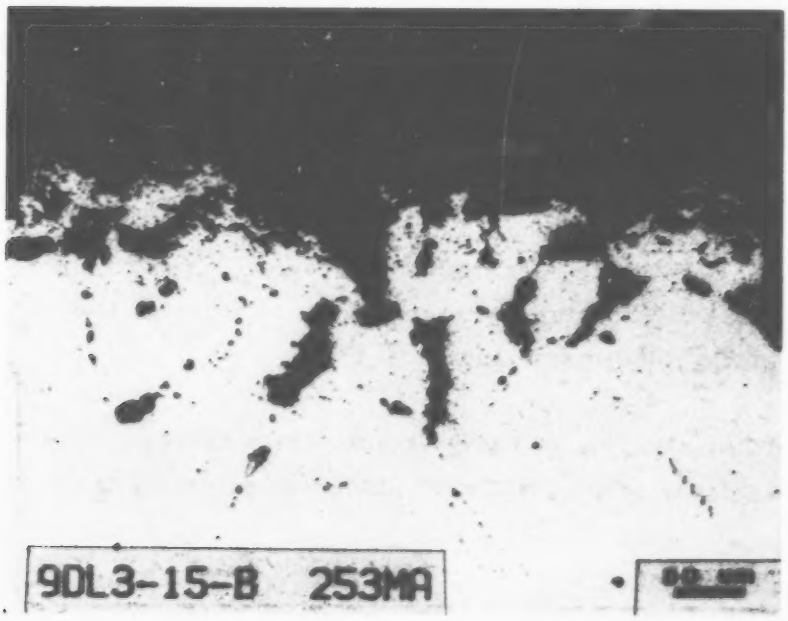
Top: Extensive non-uniform attack of surface; precipitation of oxides and globular sulphides at the grain boundaries.

Bottom: Similar to the top but the overall attack is more uniform.

Other Comments:

Precipitates throughout the alloy, but fewer in number in the zone of internal precipitation near the surface.





Photomicrographs of coupon 15 (253MA), probe 9DL3.
Top photo - position 7.4; bottom photo - position 4.0.

PROBE: 9DL3 COUPON: 16 ALLOY: 800H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	15	20	25	80	90	95	115	15
Internal Pen.	355	395	315	365	370	315	330	180
Scale	--	20	20	95	40	25	--	15
Deposit	--	--	--	--	--	--	--	--
Bore Scale	15	TR	TR	--	--	TR	TR	TR

Hardness - Before Exposure: 69 RB

After - Top: 72.0 71.2

Bottom: 71.0 70.1

Coupon Description:

Top: A few flakes of brown deposit over a white/black mottled surface.

Bottom: Mottled grey/black/white scale/deposit. Some roughness to the surface.

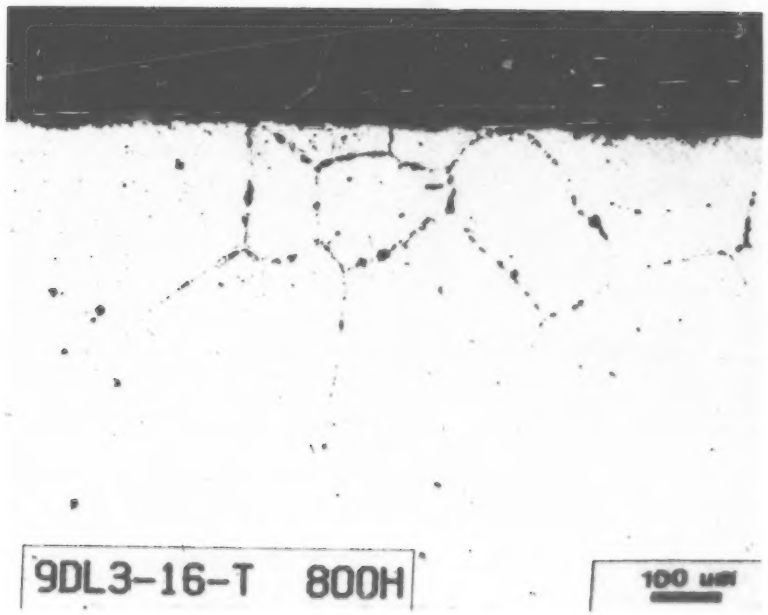
Type of Attack:

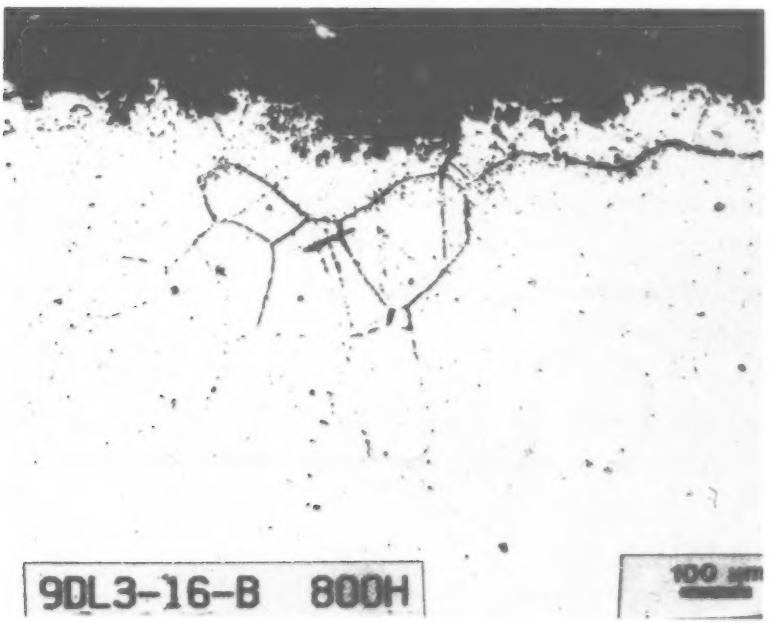
Top: Surface appears nearly unattacked; precipitation of oxides/sulphides at grain boundaries. Sides of the coupon have regions of heavier attack.

Bottom: Regions of heavy attack with a diffuse scale/metal interface; precipitation of oxides/sulphides at grain boundaries.

Other Comments:

Grain-boundary precipitates throughout alloy.





Photomicrographs of coupon 16 (800H), probe 9DL3.
Top photo - position 7.2; bottom photo - position 4.0.

PROBE: 9DL3 COUPON: 17 ALLOY: 347H

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	15	15	40	20	25	10	5	--
Internal Pen.	50	25	25	25	30	35	40	60
Scale	10	10	20	35	15	TR	10	TR
Deposit	--	--	--	--	--	--	--	--
Bore Scale	25	20	20	--	45	15	--	TR

Hardness - Before Exposure: 81 RB

After - Top: 80.9 81.8

Bottom: 79.6 78.3

Coupon Description:

Top: Uniform, dull, black scale. No obvious deposit.

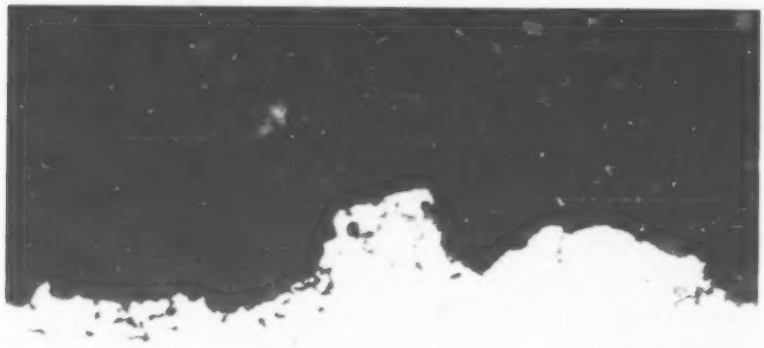
Bottom: Smooth grey/black scale/deposit.

Type of Attack:

Top: Surface appears almost unattacked in many areas. A few small oxide intrusions at grain boundaries and minor precipitation of grain-boundary globular sulphides. A few regions of somewhat heavier attack.

Bottom: A more irregular or wavy scale/metal interface than at the top with minor internal penetration/precipitation.

Other Comments:



Photomicrographs of coupon 17 (347H), probe 9DL3.
Top photo - position 0.5; bottom photo - position 4.0.

PROBE: 9DL3 COUPON: 18 ALLOY: 310

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	--	15	25	25	20	15	10	5
Internal Pen.	90	105	65	40	40	175	100	80
Scale	TR	TR	20	40	25	15	TR	30
Deposit	--	--	--	--	--	--	--	--
Bore Scale	TR	TR	TR	TR	TR	15	TR	TR

Hardness - Before Exposure: 82 RB

After - Top: 83.4 84.5

Bottom: 80.5 81.9

Coupon Description:

Top: Dull, grey/black with white spots which may be the alloy surface. A few patches of smooth surface brown deposit.

Bottom: Grey/black to red scale/deposit. Somewhat rougher surface than coupon 17.

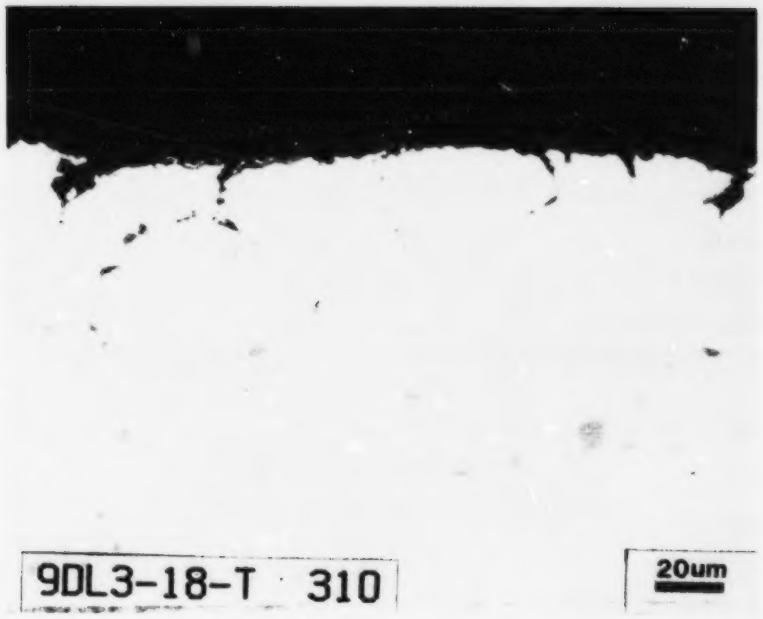
Type of Attack:

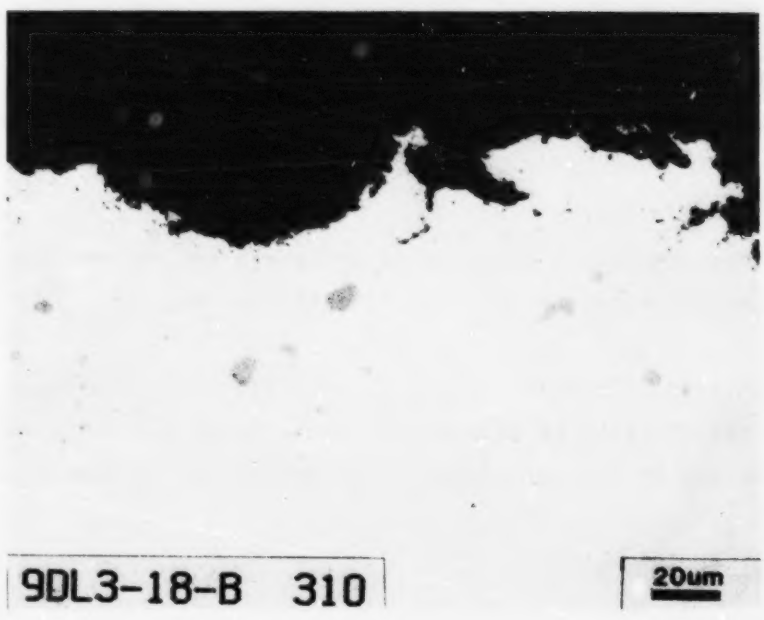
Top: Adherent thin 2 layer scale; little attack; some minor grain-boundary penetration of scale; precipitation of relatively large globular sulphides.

Bottom: Very irregular or wavy scale/metal interface; some minor grain-boundary penetration of scale. Precipitation of globular sulphides, a few regions of heavier internal attack.

Other Comments:

Precipitation of sigma and carbides throughout the alloy but these appear fewer in the zone near the surface where there is internal precipitation of globular sulphides.





Photomicrographs of coupon 18 (310), probe 9DL3.
Top photo - position 8.0; bottom photo - position 4.0.

PROBE: 9DL3 COUPON: 19 ALLOY: HK40

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	10	25	80	115	120	80	35	10
Internal Pen.	125	365	285	95	130	190	230	115
Scale	TR	25	20	15	30	60	TR	25
Deposit	--	--	--	--	--	--	--	160
Bore Scale	TR	--	--	--	--	--	--	TR

Hardness - Before Exposure: 85 RB

After - Top: 93.0 92.2

Bottom: 92.0 92.6

Coupon Description:

Top: Patches of a smooth shiny brown deposit. Brown deposit has spalled to a dull grey/black scale or to the alloy surface.

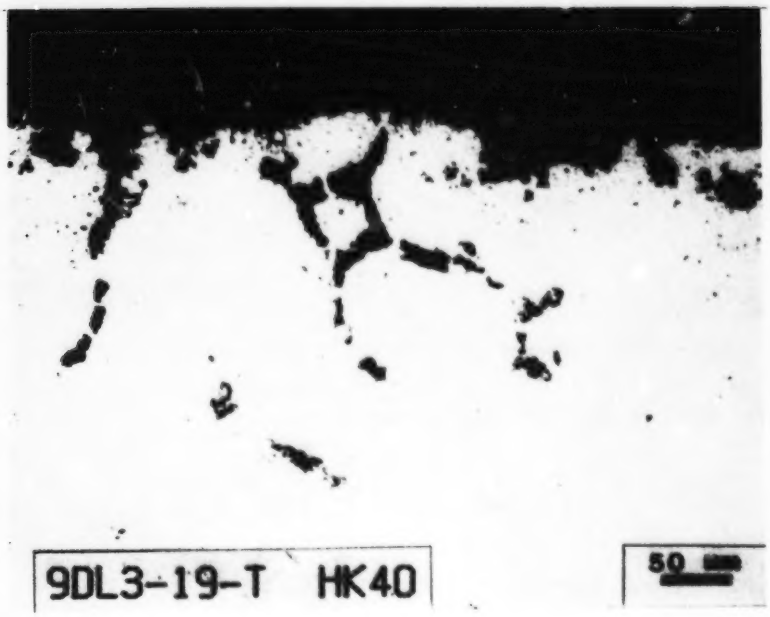
Bottom: Small patches of a dull brown deposit over a grey/black scale.

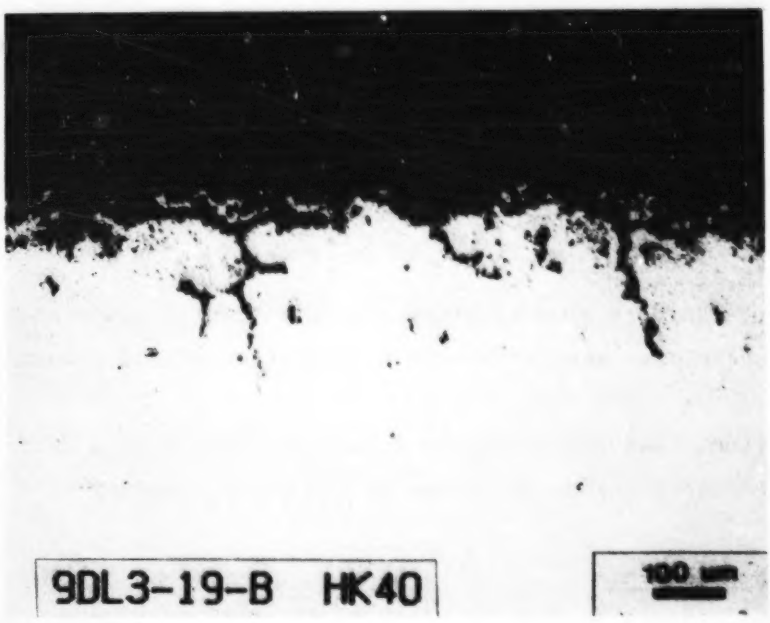
Type of Attack:

Top: Non-uniform attack of the surface with precipitation of oxides and sulphides in the interdendritic phase.

Bottom: Irregular and (in areas) diffuse scale/metal interface; precipitation of oxides and sulphides in the interdendritic phase. Attack is heavier at the sides of the coupon than at the bottom.

Other Comments:





Photomicrographs of coupon 19 (HK40), probe 9DL3.
Top photo - position 0.1; bottom photo - position 4,6.

PROBE: 9DL3 COUPON: 20 ALLOY: 253MA

EXPOSURE: 4000 h RUNS: 6 - 7 - 8 - 9

Estimated average temperature - 850 C (Bed Temperature)

Position	1	2	3	4	5	6	7	8
Metal Loss	70	210	310	255	310	305	220	15
Internal Pen.	85	190	75	110	115	150	150	125
Scale	TR	40	155	20	100	110	60	TR
Deposit	125	--	--	--	--	--	--	--
Bore Scale	20	30	25	--	35	30	TR	30

Hardness - Before Exposure: 89 RB

After - Top: 86.5 85.7

Bottom: 84.0 83.8

Coupon Description:

Top: A few patches of a shiny, brown deposit. Where spalled, a dull black scale.

Bottom: A few small patches of brown deposit; remainder of surface is covered with a grey/black scale. The east bottom seems to be heavily corroded.

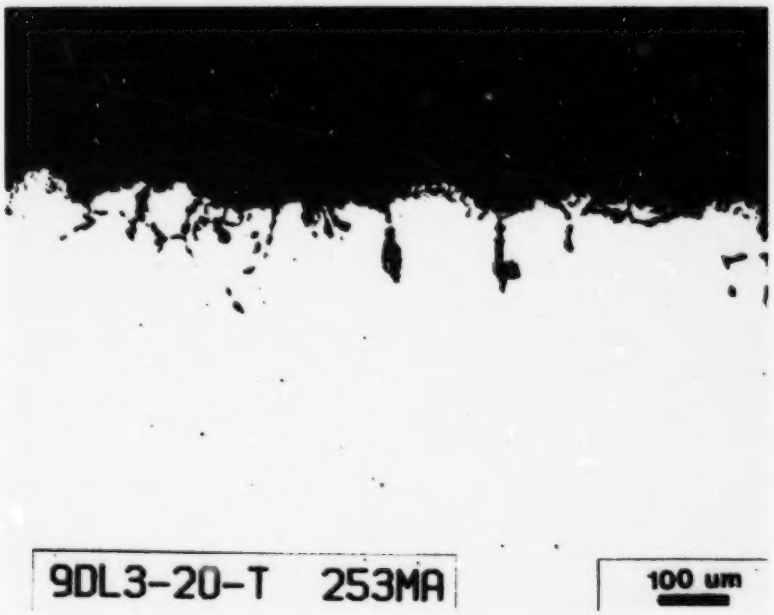
Type of Attack:

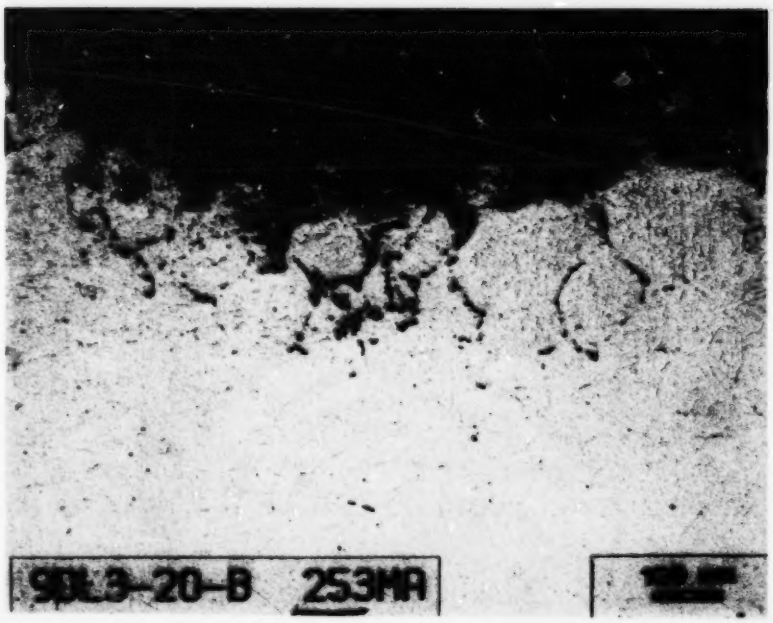
Top: Uniform zone of attack; penetration of scale at the grain boundaries. Heavier attack at the sides of the coupons.

Bottom: Heavier attack in localized areas with a diffuse scale/metal interface; oxides/sulphides at the grain boundaries.

Other Comments:

Precipitates throughout alloy that appear to be more numerous beneath areas of heavy attack. This may be an artifact of polishing.





Photomicrographs of coupon 20 (253MA), probe 9DL3.
Top photo - position 7.1; bottom photo - position 3.2.